Stereochemistry II
(Optical Isomerism)

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- **Chemistry Program**

Isomerism

In the study of organic chemistry we come across many cases when two or more compounds consist of equal number of like atoms. These compounds have the same molecular formula but differ from each other in physical or chemical properties, and are called **Isomers** and the phenomenon is called **Isomerism**. Since isomers have the same molecular formula, the difference in their properties must be due to different modes of combination or arrangement of atoms within the molecule. There are two main types of isomerism :
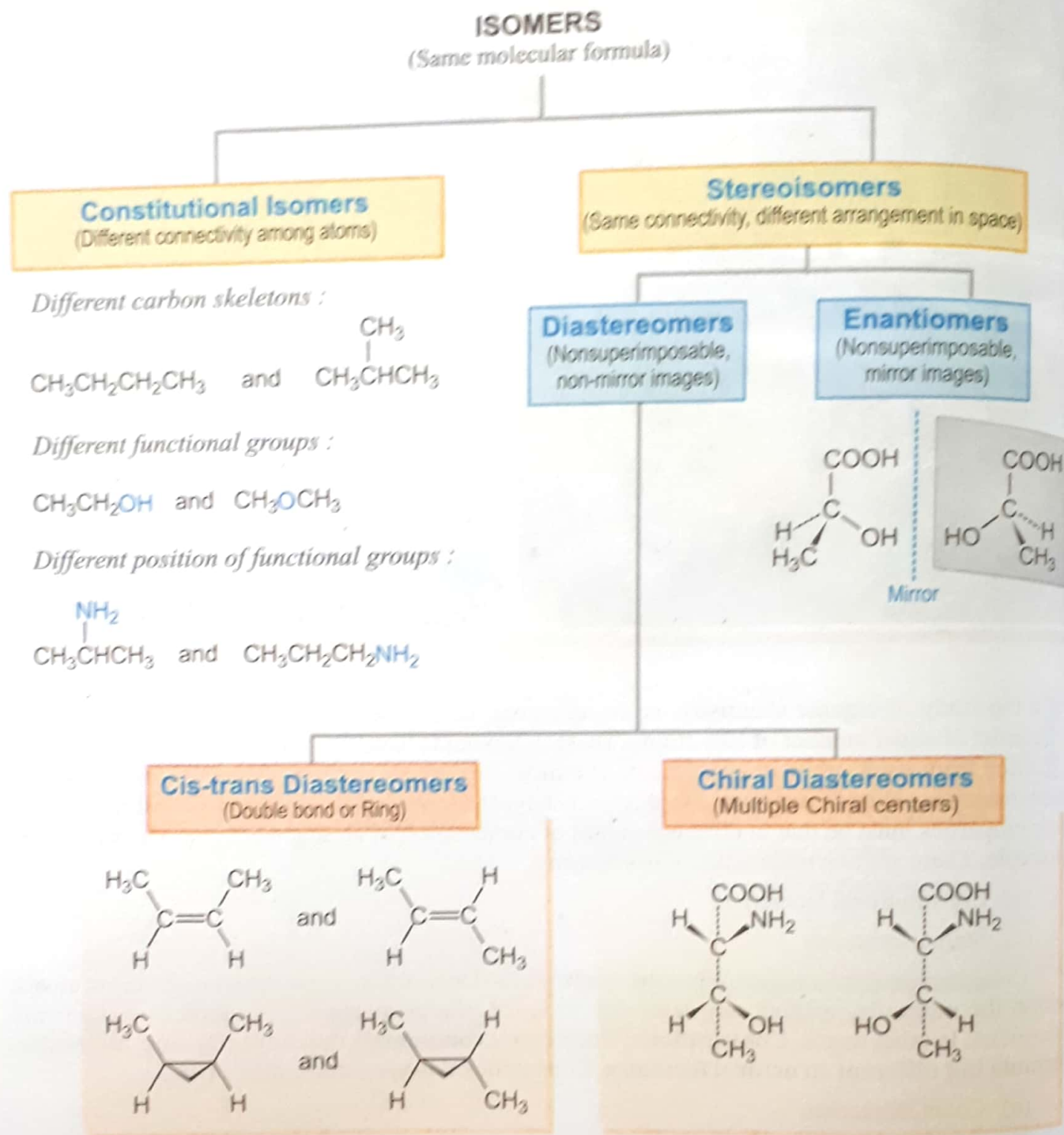
(1) Constitutional Isomerism

(2) Stereoisomerism

Constitutional Isomerism. When the isomerism is due to difference in the arrangement of atoms within the molecule, without any reference to space, the phenomenon is called *Constitutional Isomerism*. In other words, **Constitutional isomers are compounds that have the same molecular formula but different structural formulas.** Constitutional isomerism is of five types :

(a) Chain Isomerism

(b) Position Isomerism

(c) Functional Isomerism

(d) Metamerism

(e) Tautomerism

Stereoisomerism. When isomerism is caused by the different arrangements of atoms or groups in space, the phenomenon is called *Stereoisomerism*. **The stereoisomers have the same structural formulas but differ in arrangement of atoms in space.** In other words, stereoisomerism is exhibited by such compounds which have the same structural formula but differ in *configuration*. (The term configuration refers to the three-dimensional arrangement of atoms that characterizes a particular compound). Stereoisomerism is of two types :

(a) Geometrical or Cis-Trans Isomerism

(b) Optical Isomerism

ISOMERS
(Same molecular formula)

Constitutional Isomers
(Different connectivity among atoms)

Stereoisomers
(Same connectivity, different arrangement in space)

Different carbon skeletons :

$$CH_3CH_2CH_2CH_3 \quad and \quad CH_3\overset{\overset{\displaystyle CH_3}{|}}{C}HCH_3$$

Different functional groups :

$$CH_3CH_2OH \quad and \quad CH_3OCH_3$$

Different position of functional groups :

$$CH_3\overset{\overset{\displaystyle NH_2}{|}}{C}HCH_3 \quad and \quad CH_3CH_2CH_2NH_2$$

Diastereomers
(Nonsuperimposable, non-mirror images)

Enantiomers
(Nonsuperimposable, mirror images)

Mirror

Cis-trans Diastereomers
(Double bond or Ring)

Chiral Diastereomers
(Multiple Chiral centers)

CONSTITUTIONAL ISOMERISM (STRUCTURAL ISOMERISM)

In constitutional isomerism the isomers have the same molecular formula but differ in constitutional formula, that is, in the order in which the different atoms are linked in the molecule. Constitutional isomerism is of five types :

(1) Chain Isomerism

Chain isomers (also called skeletal isomers) have the same molecular formula but differ in the order in which the carbon atoms are bonded to each other.

Example 1. *n*-Butane and Isobutane

$$CH_3{-}CH_2{-}CH_2{-}CH_3$$
n-Butane

$$CH_3{-}\overset{\overset{\displaystyle CH_3}{|}}{C}H{-}CH_3$$
Isobutane
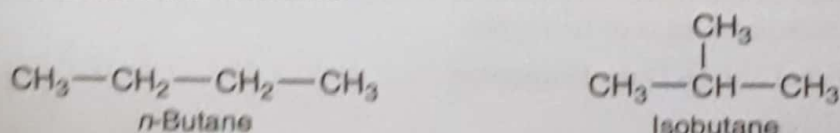
Example 2.   2-Methylbutane and 2,2-Dimethylpropane

$$CH_3-CH_2-\underset{\underset{\displaystyle CH_3}{|}}{CH}-CH_3$$

2-Methylbutane

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

2,2-Dimethylpropane
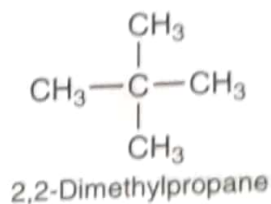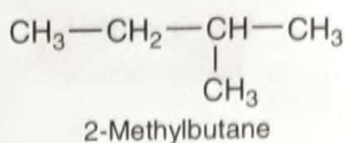
(2) Position Isomerism

Position isomers have the same molecular formula but differ in the position of a functional group on the carbon chain.
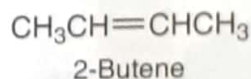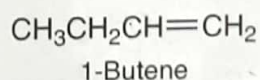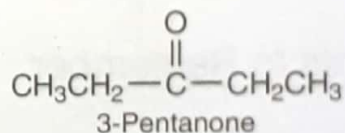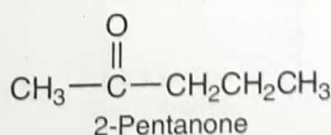
Example 1.   1-Bromobutane and 2-Bromobutane

$$CH_3CH_2CH_2CH_2Br$$

1-Bromobutane

$$CH_3\underset{\underset{\displaystyle Br}{|}}{CH}CH_2CH_3$$

2-Bromobutane
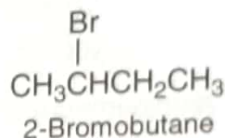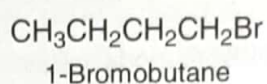
Example 2.   n-Propyl alcohol and Isopropyl alcohol

$$CH_3-CH_2-CH_2OH$$

n-Propyl alcohol

$$CH_3-\underset{\underset{\displaystyle OH}{|}}{CH}-CH_3$$

Isopropyl alcohol
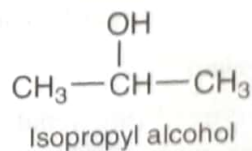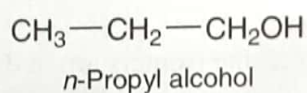
Example 3.   1-Butene and 2-Butene
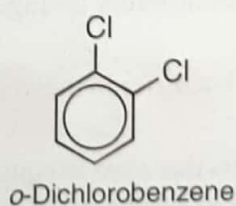
$$CH_3CH_2CH=CH_2$$

1-Butene

$$CH_3CH=CHCH_3$$

2-Butene

Example 4.   2-Pentanone and 3-Pentanone

$$CH_3-\overset{\overset{\displaystyle O}{||}}{C}-CH_2CH_2CH_3$$

2-Pentanone

$$CH_3CH_2-\overset{\overset{\displaystyle O}{||}}{C}-CH_2CH_3$$

3-Pentanone

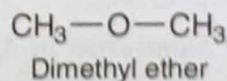**Example 5.**   o-Dichlorobenzene and m-Dichlorobenzene
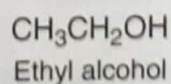

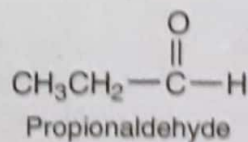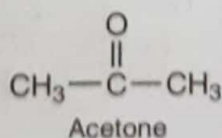o-Dichlorobenzene

m-Dichlorobenzene
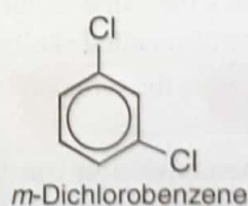
(3) Functional Isomerism

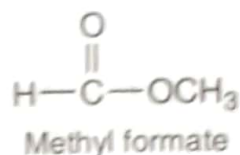Functional isomers have the same molecular formula but different functional groups.

Example 1.   Ethyl alcohol and Dimethyl ether

$$CH_3CH_2OH$$

Ethyl alcohol

$$CH_3-O-CH_3$$

Dimethyl ether

Example 2.   Acetone and Propionaldehyde

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

Acetone

$$CH_3CH_2-\overset{\overset{\displaystyle O}{||}}{C}-H$$

Propionaldehyde

Example 3. Acetic acid and Methyl formate

$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-OH$$
Acetic acid

$$H-\overset{\overset{\displaystyle O}{\|}}{C}-OCH_3$$
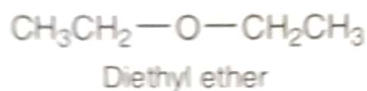Methyl formate
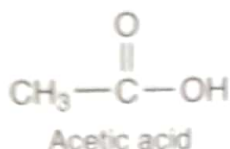
(4) Metamerism

This type of isomerism is due to the unequal distribution of carbon atoms on either side of the functional group. Members belong to the same homologous series.

Example 1. Diethyl ether and Methyl propyl ether

$$CH_3CH_2-O-CH_2CH_3$$
Diethyl ether

$$CH_3-O-CH_2CH_2CH_3$$
Methyl propyl ether
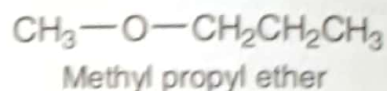
Example 2. Diethylamine and Methylpropylamine

$$CH_3CH_2-NH-CH_2CH_3$$
Diethylamine

$$CH_3CH_2CH_2-NH-CH_3$$
Methylpropylamine
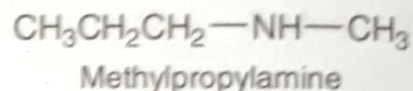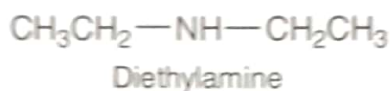
(5) Tautomerism

It is a special type of functional isomerism in which the isomers are in dynamic equilibrium with each other. For example, ethyl acetoacetate is an equilibrium mixture of the following two forms. At room temperature, the mixture contains 93% of keto-form plus 6% of the enol-form.

$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-CH_2CO_2C_2H_5$$
Keto-Form

$$\rightleftharpoons$$

$$CH_3-\overset{\overset{\displaystyle OH}{|}}{C}=CH-CO_2C_2H_5$$
Enol-Form

Points to Remember

1. Constitutional isomers are also called structural isomers.
2. Chain isomers have the same molecular formula but different arrangement of carbon atoms. Chain isomers are also called skeletal isomers.
3. Position isomers have the same molecular formula but differ in the position of a substituent or functional group.
4. Tautomers are interconvertible constitutional isomers that exist in equilibrium with each other.

GEOMETRICAL ISOMERISM

Geometrical isomerism (also called *cis-trans* isomerism) results from a restriction in rotation about double bonds, or about single bonds in cyclic compounds.

(1) Geometrical Isomerism in Alkenes

The carbon atoms of the carbon-carbon double bond are sp^2 hybridized. The carbon-carbon double bond consists of a σ bond and a π bond. The σ bond is formed by the overlap of sp^2 hybrid orbitals. The π bond is formed by the overlap of p orbitals. The presence of the π bond locks the molecule in one position. The *two* carbon atoms of the C=C bond and the *four* atoms that are attached to them lie in one plane and their positions in space are fixed. Rotation around the C=C bond is not possible because rotation would break the π bond (Fig. 7.1).
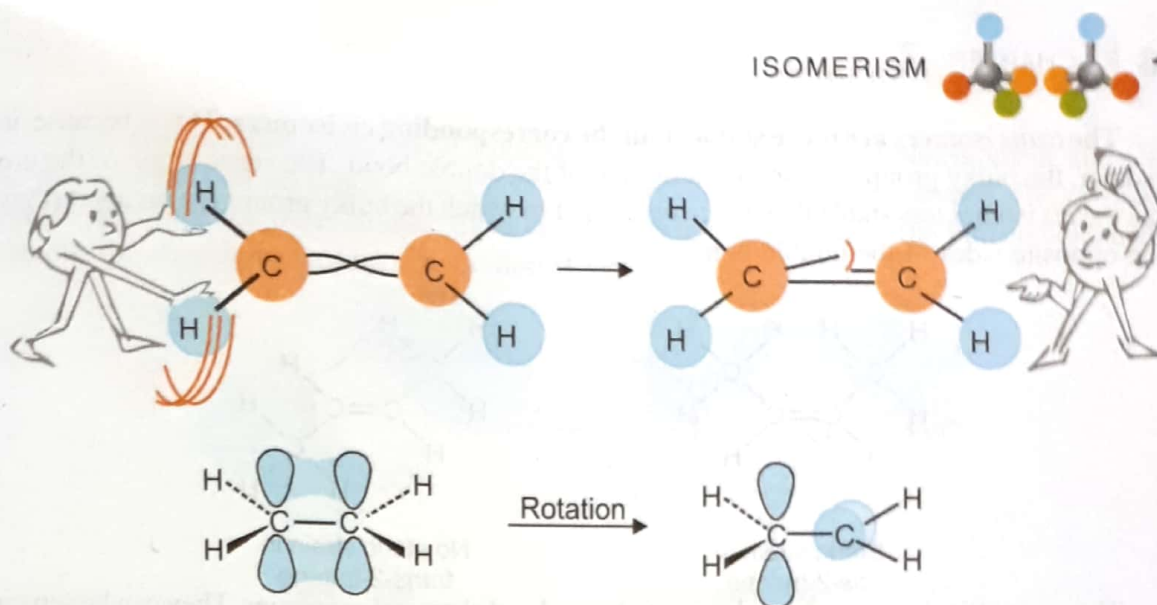
Fig.7.1 Rotation about π bond is not possible because it would break the π bond.

This restriction of rotation about the carbon-carbon double bond is responsible for the geometrical isomerism in alkenes. A popular analogy for this situation is based upon two boards and two nails. Driving one nail through two boards will not prevent free rotation of the two boards. But once a second nail is used, the boards cannot be freely rotated.


Free rotation is not possible   Free rotation is possible
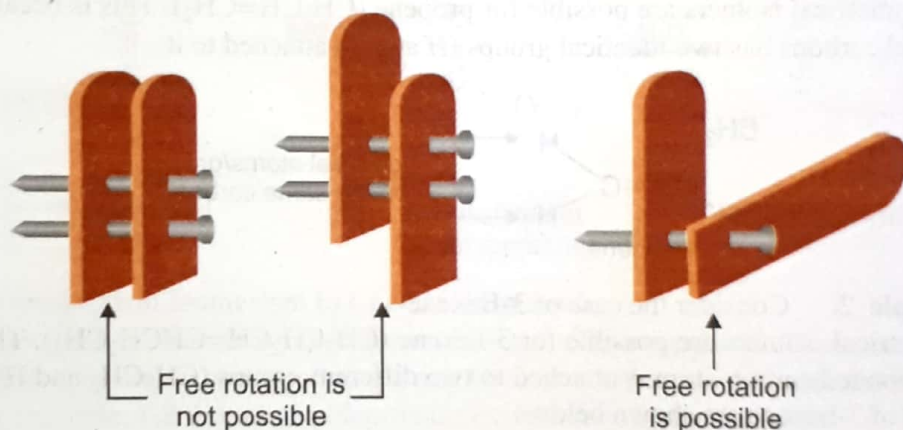
Consider the case of 2-butene. It exists in two spacial arrangements :

cis-2-Butene
(bp 4°C)

and

trans-2-Butene
(bp 1°C)
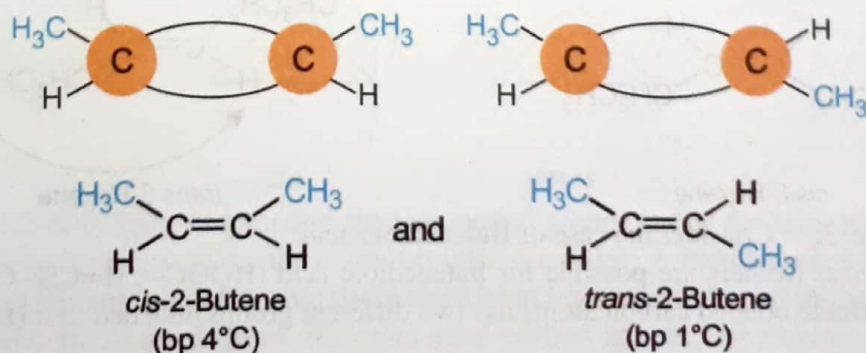
These two compounds are referred to as geometrical isomers and are distinguished from each other by the terms *cis* and *trans*. **The *cis* isomer is one in which two similar groups are on the same side of the double bond. The *trans* isomer is that in which two similar groups are on the opposite sides of the double bond.** Consequently, this type of isomerism is often called *cis-trans* isomerism. Geometrical isomers are stereoisomers, because they have the same structural formula but different spacial arrangement of atoms.

The *trans* isomers are more stable than the corresponding cis isomers. This is because, in the cis isomer, the bulky groups are on the same side of the double bond. The steric strain of the groups makes the *cis* isomer less stable than the *trans* isomer in which the bulky groups are far apart (they are on the opposite sides of the double bond).
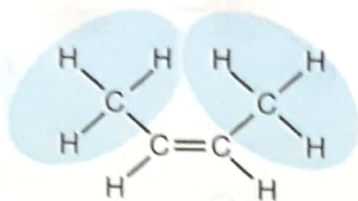

Steric strain in
cis-2-butene
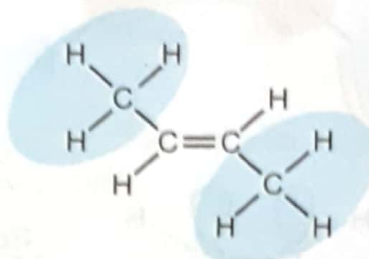
No steric strain in
trans-2-butene

The geometrical isomers have different physical and chemical properties. They can be separated by conventional techniques like fractional distillation, gas chromatography etc.

All alkenes do not show geometrical isomerism. Geometrical isomerism is possible only when each double bonded carbon atom is attached to two different atoms or groups. The following examples illustrate this condition for the existence of geometrical isomers.

Example 1. Consider the case of Propene

No geometrical isomers are possible for propene ($CH_3CH=CH_2$). This is because one of the double bonded carbons has two identical groups (H atoms) attached to it.
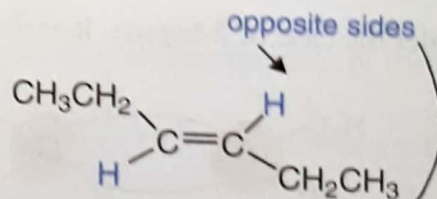

Identical atoms/groups
on the same carbon

Propene
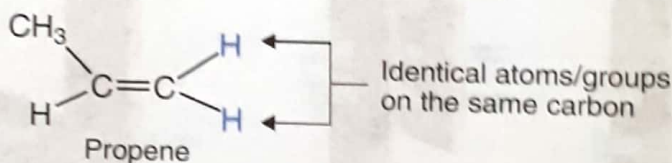
Example 2. Consider the case of 3-Hexene

Geometrical isomers are possible for 3-hexene ($CH_3CH_2CH=CHCH_2CH_3$). This is because each double bonded carbon atom is attached to two different groups (CH_3CH_2 and H). The *cis* and *trans* isomers of 3-hexene are shown below :
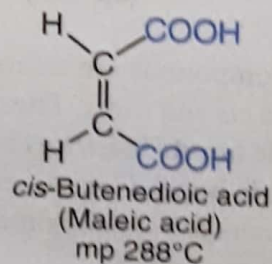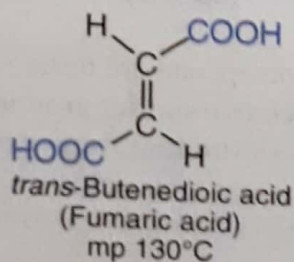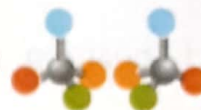
same side

opposite sides
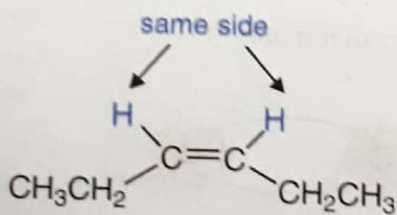
cis-3-Hexene

trans-3-Hexene

**Example 3.** Consider the case of Butenedioic acid

Geometrical isomers are possible for butenedioic acid (HOOC–CH=CH–COOH). This is because each double bonded carbon atoms has two different groups attached to it (H and COOH).

trans-Butenedioic acid
(Fumaric acid)
mp 130°C

cis-Butenedioic acid
(Maleic acid)
mp 288°C

These isomers differ in physical properties such as melting point, dipole moment, and acidities. The *trans*-isomer has no dipole, since it is symmetrical, unlike the *cis*-isomer. The *cis*-isomer is stronger acid than the *trans*-isomer. Even chemical properties differ in the butenedioic acids. For example, the *cis*-acid undergoes dehydration at 100°C.


Maleic acid   Maleic anhydride
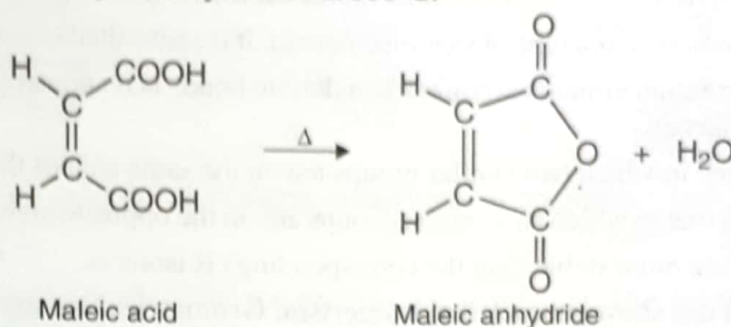
However, the *trans*-acid does not form an anhydride until heated to 240°C. At that temperature there is sufficient thermal energy to break the double bond, so that the *cis*-acid and the anhydride are formed in succession.

Fumaric acid   (not isolated at   Maleic anhydride
   this temperature)
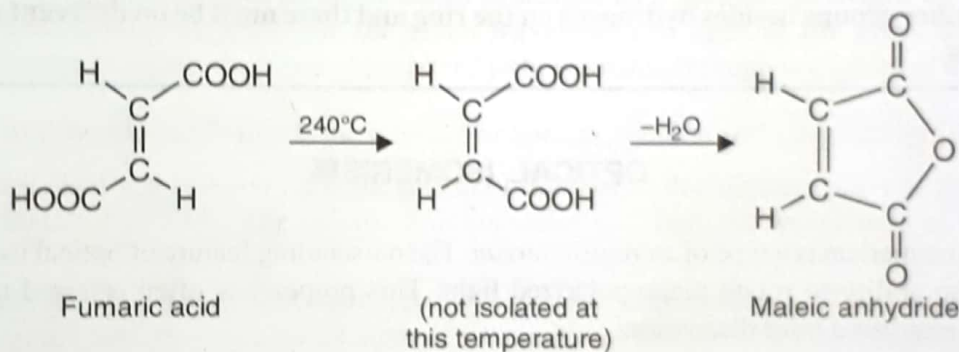
(2) Geometrical Isomerism in Cyclic Compounds

Geometrical isomerism is also possible in cyclic compounds. There can be no rotation about carbon-carbon single bonds forming a ring because rotation would break the bonds and break the ring. For example, 1,2-dimethylcyclopropane exists in two isomeric forms.

cis   trans
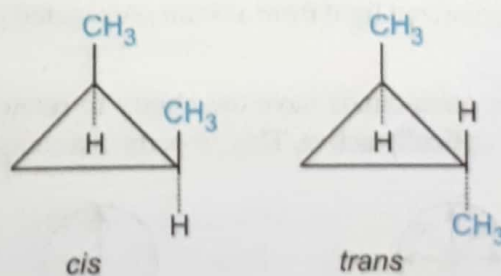
In *cis*-1,2-dimethylcyclopropane, the two methyl groups are on the same side of the ring. In *trans*-1,2-dimethylcyclopropane, they are on opposite sides. **A requirement for geometrical isomerism in cyclic compounds is that there must be at least two other groups besides hydrogens on the ring and these must be on different ring carbon atoms.** For example, no geometrical isomers are possible for 1,1-dimethylcyclopropane.

No geometrical isomers are possible for this compound

Geometrical isomers are possible for this compound
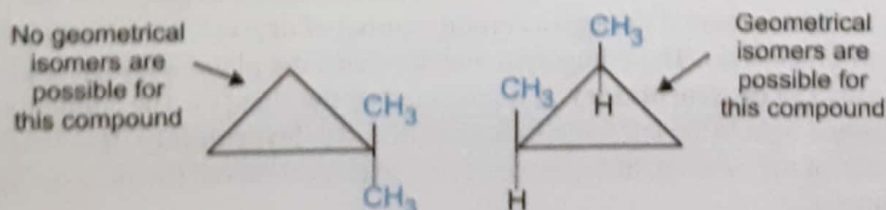
OPTICAL ISOMERISM

Optical isomerism is a type of *stereoisomerism*. The outstanding feature of optical isomers is that they have the ability to rotate plane-polarized light. This property is often referred to as optical activity and requires a brief discussion.

OPTICAL ACTIVITY - PLANE-POLARIZED LIGHT

Light from ordinary electric lamp is composed of waves vibrating in many different planes. When it is passed through Nicol prism (made of calcite, $CaCO_3$) or polaroid lense, light is found to vibrate in only one plane, and is said to be **plane-polarized** or simply polarized. The diagrams illustrate the vibrations of ordinary and polarized light from a beam propagated perpendicularly to the plane of paper.

Solutions of some organic compounds have the ability to rotate the plane of polarized light. These compounds are said to be **optically active**. This property of a compound is called **optical activity**.

Ordinary Light

Plane-Polarized Light
(Polarized Light)

Optical activity in a compound is detected and measured by means of a **polarimeter**. When a solution of a known concentration of an optically active material is placed in the polarimeter, the beam of polarized light is rotated through a certain number of degrees, either to the right (*clockwise*) or to the left (*anti-clockwise*). The compound which rotates the plane of polarized light to the right (clockwise) is said to be **dextrorotatory**. It is indicated by the sign (+). The compound which rotates the plane of polarized light to the left (anticlockwise) is said to **levorotatory**. It is indicated by the sign (−). The magnitude of the rotation, in degrees, is referred to as observed rotation, α. Fig. 7.2 shows the parts of a polarimeter.
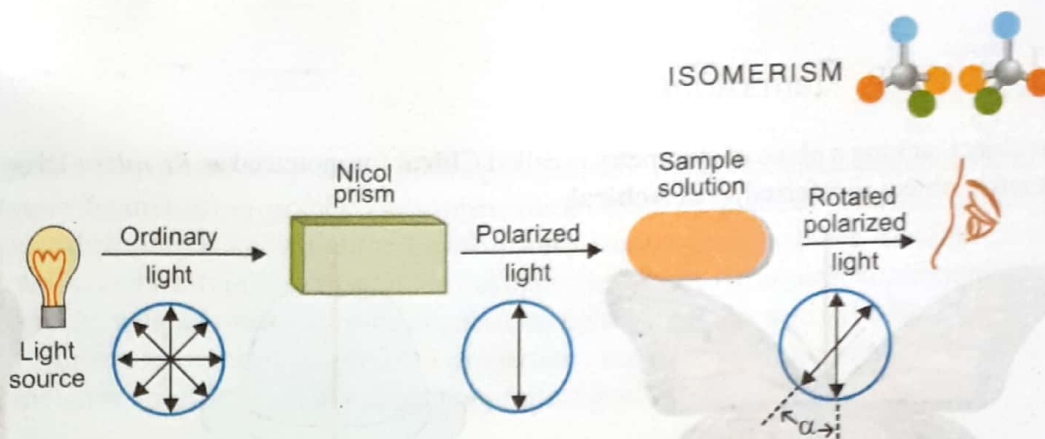
Fig.7.2. A simple polarimeter in operation.

SPECIFIC ROTATION

Optically active compounds rotate the plane of polarized light. The degree of rotation depends upon the number of molecules of the compound encountered by light along its path. It is, therefore, necessary to introduce some standard by which the rotating powers of different compounds may be compared.

Specific rotation is defined as the rotation produced by a solution of length 10 centimeters and unit concentration (1 g/ml) for the given wavelength of light at the given temperature. Consider a system in which the plane of polarized light is rotated through α degrees at a temperature of t°C and using the sodium D-line as the source. The specific rotation $[\alpha]_D^t$ is given by $[\alpha]_D^t = \dfrac{100\alpha}{lc}$

where α is the observed rotation ; l is the length of the tube in decimeters ; and c is the number of grams per 100 ml of solution. The specific rotation varies with both the wavelength of light and the temperature.

Problem. A 1.20 g sample of cocaine, $[\alpha]_D = -16°$, was dissolved in 7.50 ml of chloroform and placed in a sample tube having a path length of 5.0 cm. What was the observed rotation ? Is cocaine dextrorotatory or levorotatory ?

Solution. Use the following relationship :

$$[\alpha]_D^t = \frac{\alpha}{l \times c}$$

Where, α = observed rotation in degrees

l = length of tube (dm) = path length

c = concentration of sample (g/ml)

The given values are :

$[\alpha]_D^t = -16°$

$\alpha = $?

$l = 5.0 \text{ cm} = 0.50 \text{ dm} \ (1 \text{ dm} = 10 \text{ cm})$

$c = 1.20 \text{ g}/7.50 \text{ ml} = 0.160 \text{ g/ml}$

Thus, $-16° = \dfrac{\alpha}{0.50 \times 0.160}$

$\alpha = -16° \times 0.50 \times 0.160$

$= -1.3°$

The observed rotation is $-1.3°$.

Cocaine is levorotatory.

PLANE OF SYMMETRY

A plane which divides an object into two symmetrical halves, is said to be *plane of symmetry*. For example, a person or a hat has a plane of symmetry (Fig. 7.3). A person's hand or gloves lack a plane of symmetry.

An object lacking a plane of symmetry is called **Chiral** (pronounced as *Ki-ral*) or **Dissymmetric.** A symmetric object is referred to as **Achiral**.
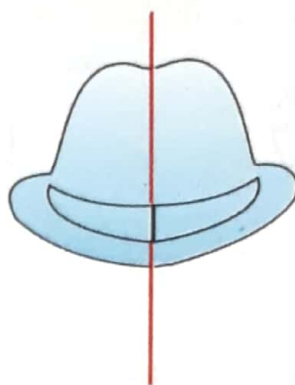
Plane of symmetry

Fig. 7.3. Planes of symmetry.

A chiral object cannot be superimposed on its mirror image. A left hand, for example, does not possess a plane of symmetry, and its mirror image is not another left hand but a right hand (Fig. 7.4). The two are not identical, because they cannot be superimposed. If we were to lay one hand on top of the other, the fingers and the thumbs would clash.
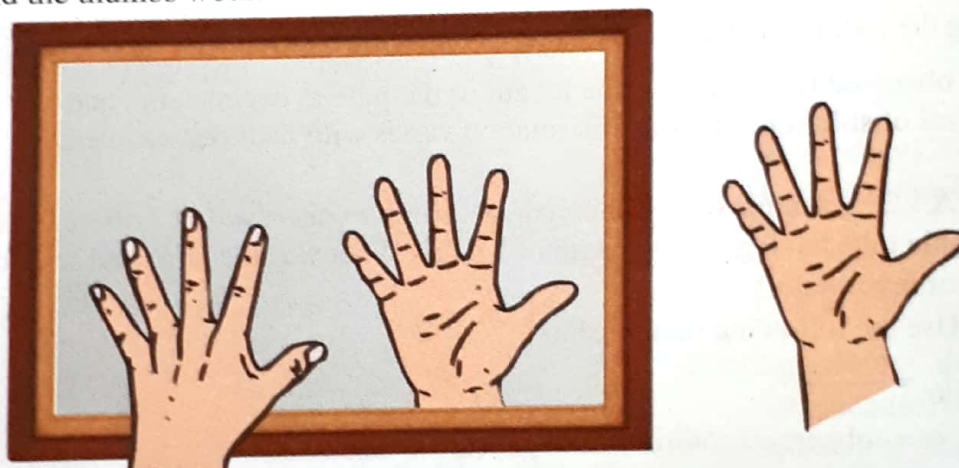
Fig. 7.4. The mirror image relationship of the left and right hands.
Notice that right hand is the mirror image of the left hand.

CHIRAL (OR ASYMMETRIC) CARBON ATOM

A carbon atom which is bonded to four different groups is called a **Chiral (or Asymmetric) Carbon Atom.** For example,

Chiral carbon CH_2CH_3

$$CH_3 - \overset{\displaystyle |}{\underset{\displaystyle |}{C}} - CH_2CH_2CH_3$$
$$Br$$

Chiral carbon CO_2H

$$H - \overset{\displaystyle |}{\underset{\displaystyle |}{C}} - OH$$
$$CH_2OH$$
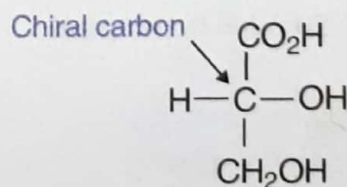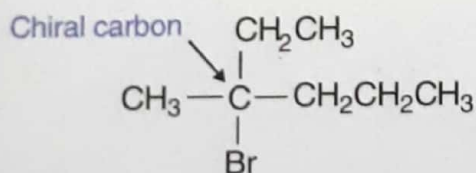
The term **chiral** (Greek **handedness**; pronounced **kairal**) carbon atom means that a carbon atom is bonded to four different groups and that a molecule of this type lacks a plane of symmetry. Such a molecule is also called **Asymmetric or Dissymmetric.**

OPTICAL ISOMERISM

A substance which has the ability to rotate the plane of polarized light is said to be *optically active* and exhibits *optical isomerism.* **Optical isomers are isomers that are identical in all properties except for their effect on plane of polarized light.**
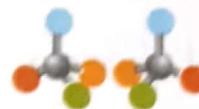
The isomer which rotates the plane of polarized light to the right (clockwise direction) is known as **Dextrorotatory Isomer** or (+)-isomer. The isomer which rotates the plane of polarized light to the left (anticlockwise direction) is known as the **Levorotatory Isomer** or (−)-isomer. The optical rotatory powers of two isomers are equal in magnitude but opposite in sign. An equimolar mixture of the two isomers, therefore, will not rotate the plane of polarized light at all and is said to be **Racemic Mixture.**

Optical isomers have the same physical properties : melting point, boiling point, density, etc. They have the same specific rotation but with opposite signs.

OPTICAL ISOMERISM OF LACTIC ACID

Lactic acid (2-Hydroxypropanoic acid) is an example of a compound which shows optical isomerism. It contains one chiral carbon atom.

$$CH_3-\overset{\overset{\displaystyle OH}{|}}{\underset{\underset{\displaystyle H}{|}}{C^*}}-COOH$$
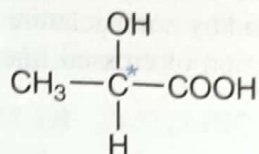
Lactic acid. The chiral carbon is shown by an asterisk.

Two three dimensional structures are possible for Lactic acid (Fig. 7.5).

These structures are not identical because they cannot be superimposed on each other. One is the mirror image of the other. Such nonsuperimposable mirror image forms are optical isomers and are called *enantiomers*. Thus, three forms of lactic acid are known. Two are optically active and the third is optically inactive.
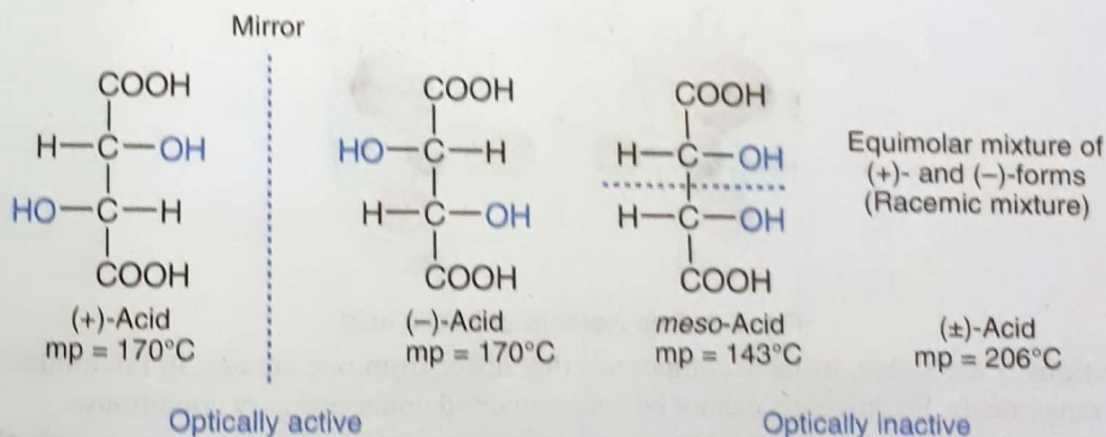
1. **(+)-Lactic Acid**. It rotates the plane of polarized light to the right (clockwise direction) and is called dextrorotatory.

2. **(−)-Lactic Acid**. It rotates the plane of polarized light to the left (anticlockwise direction) and is called levorotatory. (−)-Lactic acid is the mirror image of (+)-lactic acid and *vice versa*.

3. **(±)-Lactic Acid**. It does not rotate the plane of polarized light. That is, it is optically inactive. It is an equimolar mixture of (+)-and (−)-forms (racemic mixture).
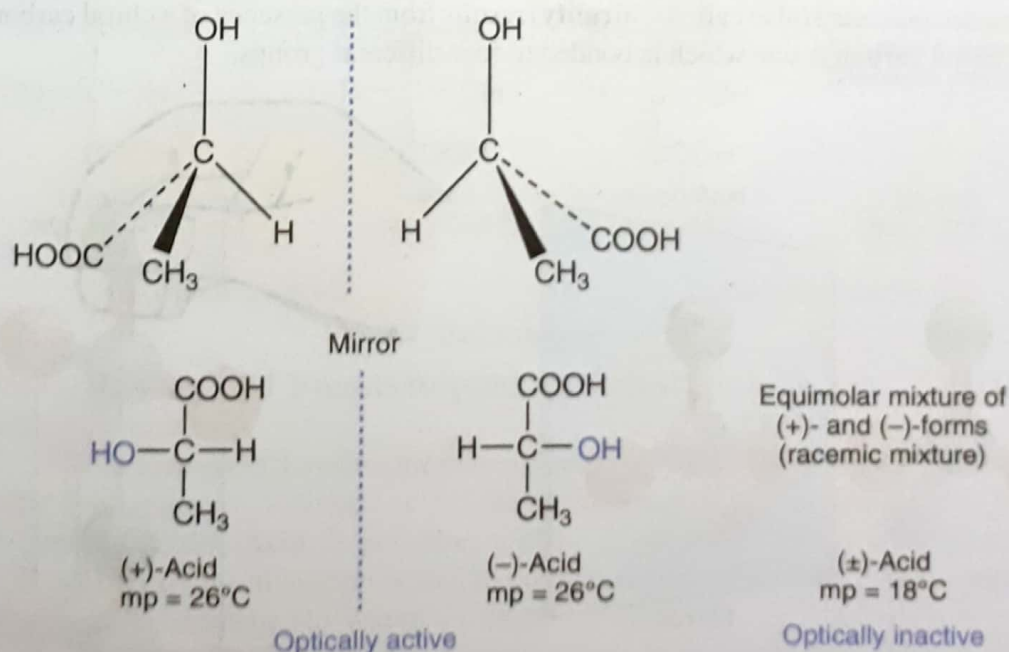
Fig. 7.5. Isomers of Lactic acid. In the upper line two three-dimensional structures are shown. In the lower line a commonly used Fischer projection is given. The vertical lines represent bonds going away from the observer/reader and horizontal lines represent bonds coming toward the observer.

FISCHER PROJECTIONS

Fischer projections provide an easy way to draw three-dimensional molecules on paper. All atoms are projected onto one plane. The Fischer projection of one of the enantiomers of lactic acid is shown below :

$$
\begin{array}{c}
COOH \\
| \\
HO-C-H \\
| \\
CH_3
\end{array}
\quad\equiv\quad
\begin{array}{c}
COOH \\
HO-\!\!-\!\!-H \\
CH_3
\end{array}
$$

Fischer projection of (+)-Lactic acid.

The **Fischer rules** for showing the arrangement around a chiral carbon are as follows:

1. The carbon chain of the compound is arranged vertically, with the most oxidized carbon at the top. Or, put the carbon number *1* (as defined by nomenclature rules) at the top.
2. Represent the chiral carbon(s) at the intersection of crossed lines. Some teachers like to show the chiral carbon also.
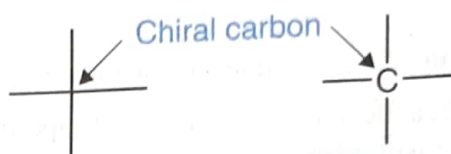
Chiral carbon

3. Groups attached to the vertical lines are understood to be going back behind the plane of the paper. That is, the vertical lines represent bonds going away from the observer. The chiral carbon is in the paper plane.
4. Groups attached to the horizontal lines are understood to be coming forward out of the paper plane. That is, the horizontal lines represent bonds coming toward the observer.

CONDITION FOR OPTICAL ISOMERISM

The necessary condition for a molecule to exhibit optical isomerism is that it should be *dissymmetric*. That is, the molecule should not be superimposable on its mirror image. In simple molecules, the dissymmetry (also called **Chirality**) results from the presence of a chiral carbon atom. Recall that a chiral carbon is one which is bonded to four different groups.
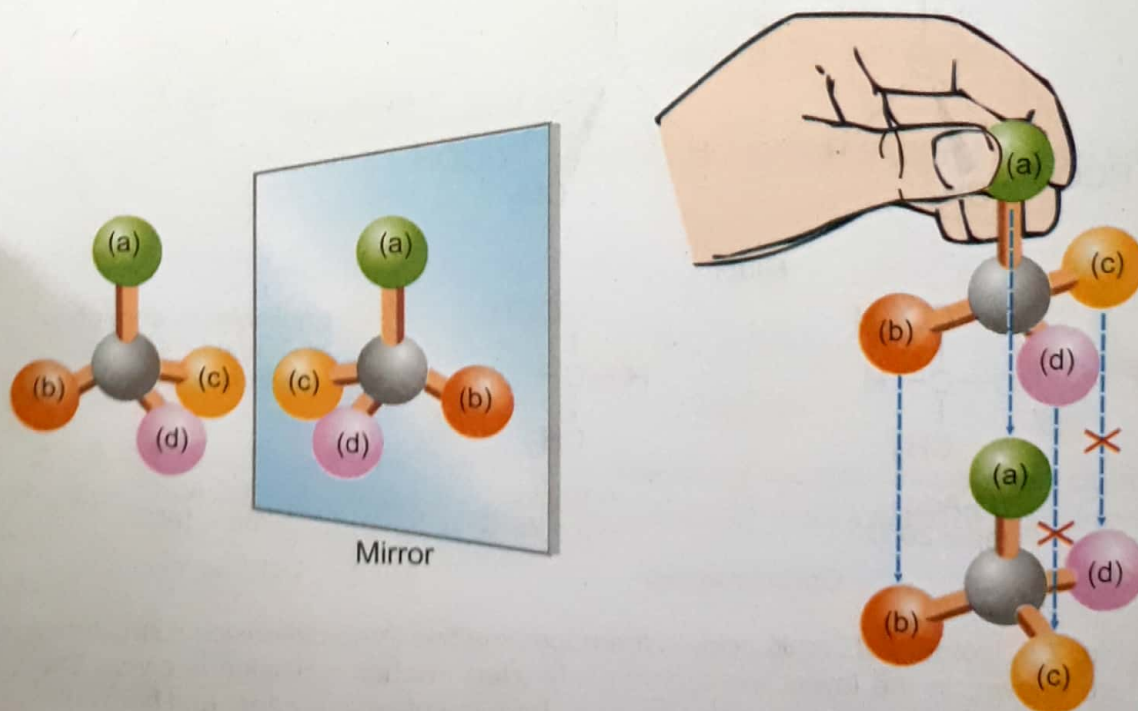
Fig. 7.6. The two forms (I and II) of C_{abcd} are nonsuperimposable.

Consider a chiral molecule C_abcd. Fig. 7.6 shows two three dimensional models for this molecule. The form (II) is the mirror image of (I) and the two cannot be superimposed. If you try to superimpose the four groups attached to a chiral carbon atom in form (I) and form (II), only two of the four groups coincide, while the other two are in conflict. This shows that the two forms represent different compounds.

The nonsuperimposable mirror image forms of a chiral molecule are called **Enantiomers** (Greek, *enantio* = opposite). They represent two optical isomers : (+) and (–). Their opposite rotatory powers are due to the opposite arrangements of groups around the asymmetric carbon atom.

It is true that most of the compounds which contain chiral carbon atoms show optical isomerism. But it is not always so. There are some compounds (such as *meso*-tartaric acid) which have asymmetric carbons but being *achiral*, do not show optical isomerism. On the other hand, there are certain compounds (such as substituted allenes and biphenyls) which have no chiral carbons but being dissymmetric, show optical isomerism.

OPTICAL ISOMERISM OF TARTARIC ACID

Tartaric acid (2,3-Dihydroxybutanedioic acid) contains two chiral carbon atoms.

$$
\begin{array}{c}
OH \\
| \\
H-\overset{*}{C}-COOH \\
| \\
H-\overset{*}{C}-COOH \\
| \\
OH
\end{array}
$$
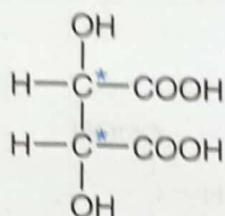
Tartaric acid. The two chiral carbons are shown by asterisks.

Four forms of tartaric acid are known (Fig. 7.7). Two of them are optically active and two are optically inactive. The optically active forms are related to each other as an object to its mirror image. That is, they are *enantiomers*.

Mirror

| (+)-Acid | (–)-Acid | meso-Acid | (±)-Acid |
| mp = 170°C | mp = 170°C | mp = 143°C | mp = 206°C |

Equimolar mixture of (+)- and (–)-forms (Racemic mixture)

Optically active   Optically Inactive

Fig. 7.7. Isomers of tartaric acid.

1. **(+)-Tartaric Acid**. It rotates the plane of polarized light to the right (clockwise direction) and is called dextrorotatory.

2. **(–)-Tartaric Acid**. It rotates the plane of polarized light to the left (anticlockwise direction) and is called levorotatory. (–)-Tartaric acid is the mirror image of (+)-tartaric acid and *vice versa*.

3. ***meso*-Tartaric Acid**. It possesses a plane of symmetry and is consequently optically inactive. This optically inactive form is said to be *internally compensated* (Optical rotation of one asymmetric carbon is cancelled by that of the other).

4. **(±)-Tartaric Acid**. It does not rotate the plane of polarized light. That is, it is optically inactive. It is an equimolar mixture of (+)- and (–)-forms (racemic mixture).

A molecule containing n chiral centres can give rise to a maximum of 2^n optical isomers, unless the compound has a *meso* form, in which case it is $2^n - 1$. For example, *four optical* isomers are possible for 2-bromo-2-butanol. It has *two* chiral carbon atoms but no plane of symmetry (Fig. 7.8).

$$
\begin{array}{cc}
\text{CH}_3 & \text{CH}_3 \\
| & | \\
\text{H—C—OH} & \text{HO—C—H} \\
| & | \\
\text{Br—C—H} & \text{H—C—Br} \\
| & | \\
\text{CH}_3 & \text{CH}_3 \\
(A) & (B)
\end{array}
\qquad
\begin{array}{cc}
\text{CH}_3 & \text{CH}_3 \\
| & | \\
\text{H—C—OH} & \text{HO—C—H} \\
| & | \\
\text{H—C—Br} & \text{Br—C—H} \\
| & | \\
\text{CH}_3 & \text{CH}_3 \\
(C) & (D)
\end{array}
$$
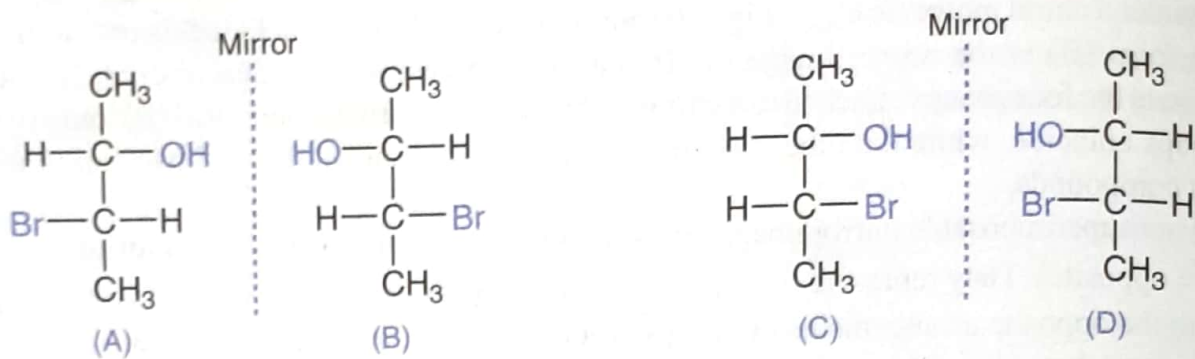
Fig. 7.8. Four isomers of 3-Bromo-2-butanol.

Optical isomers which are not enantiomers (mirror images) such as (A) and (C) or (B) and (D) of the above example, are known as **Diastereomers**.

PROPERTIES OF ENANTIOMERS

Optical isomers that are mirror images are called **Enantiomers**. These always exist as discrete pairs. For example, there are two optical isomers of lactic acid (Fig. 7.9). Notice that (A) is the mirror image of (B). They are a pair of enantiomers.

Mirror

$$
\begin{array}{cc}
\text{COOH} & \text{COOH} \\
| & | \\
\text{HO—C—H} & \text{H—C—OH} \\
| & | \\
\text{CH}_3 & \text{CH}_3 \\
(A) & (B)
\end{array}
$$
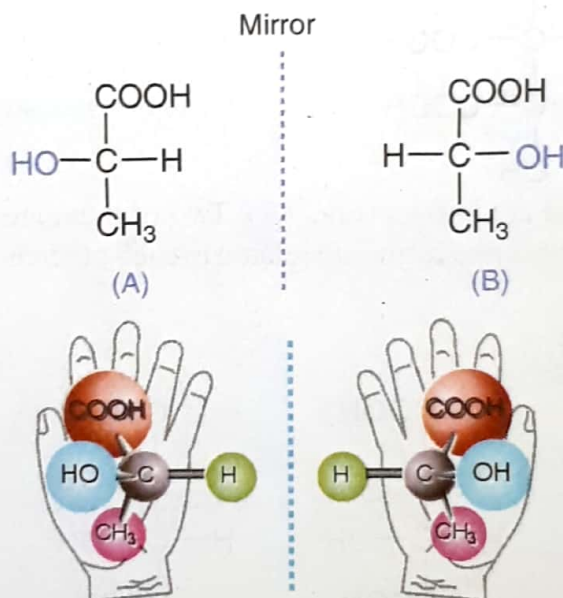
Fig. 7.9. Two isomers of Lactic acid.

Enantiomers are stable, isolable compounds that differ from one another in three-dimensional spatial arrangements. Enantiomers cannot be interconverted under ordinary conditions.

Enantiomers have identical properties in all respects except in their interaction with plane of polarized light. Enantiomers have the same melting point, density, solubility, color, and reactivity toward acids and bases. They differ, however, in the direction in which they rotate the plane of polarized light. Both rotate the plane of polarized light to exactly the same extent (same angle) but one rotates the plane to the right (clockwise ; called *dextrorotatory*), while the other rotates the plane to the left (anticlockwise ; called *levorotatory*).

A mixture of equal amounts of two enantiomers is called a **Racemic Mixture**. Such a mixture is optically inactive (does not rotate the plane of polarized light) because the two components rotate the plane of polarized light equally in opposite directions and cancel one another.

PROPERTIES OF DIASTEREOMERS

In general, each chiral carbon atom in a molecule doubles the number of theoretically possible isomers. Hence, molecule with n chiral carbon atoms should have 2^n stereoisomers. Fig. 7.10 shows the four isomers of 3-bromo-2-butanol, which has *two* chiral carbon atoms.

Notice that (A) is the mirror image of (B) ; (C) is the mirror image of (D). Thus the four isomers are two pairs of *enantiomers*. Now compare (A) with (C). They are neither superimposable nor are they mirror images. They are called *diastereomers*. (A) and (D) are also diastereomers, as are (B) and (C), and (B) and (D). Stereoisomers that are not mirror images of each other are called **Diastereomers**.

Mirror

CH_3

H—C—OH   HO—C—H

Br—C—H   H—C—Br

CH_3 CH_3

(A)   (B)

Mirror

CH_3

H—C—OH   HO—C—H

H—C—Br   Br—C—H

CH_3 CH_3

(C)   (D)
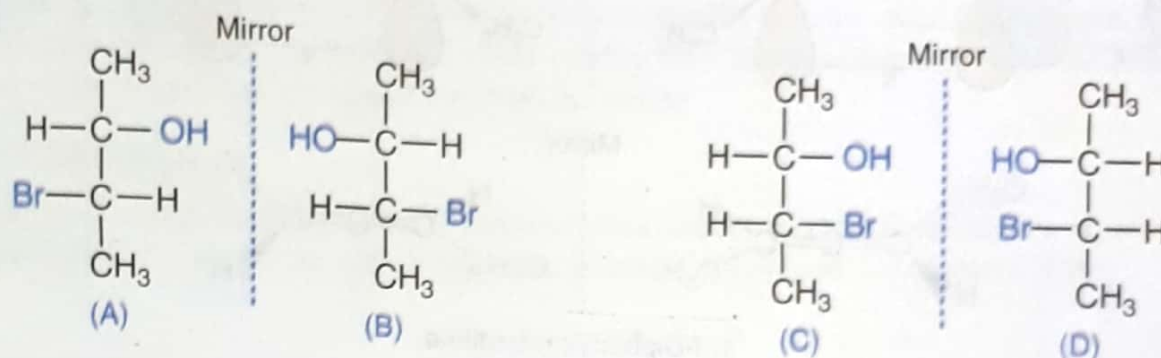
Fig. 7.10. Four isomers of 3-Bromo-2-butanol.

Diastereomers have different properties. Two diastereomers will have different melting points, boiling points, and solubilities. They will have different chemical reactivities toward most reagents.

PROPERTIES OF MESO COMPOUNDS

A compound with two or more chiral carbon atoms but also having a plane of symmetry (a mirror plane) is called the **Meso Compound**. Fig. 7.11 shows two meso compounds. These molecules have planes of symmetry dividing them midway between the two chiral carbons in each. Notice that one-half of the molecule is the mirror image of the other. Both molecules are optically inactive, even though each has two chiral centres. Neither will rotate the plane polarized light.

Plane of symmetry

H

H_3C—C—OH

H_3C—C—OH

H

meso-2,3-Dihydroxybutane

O=C—OH

H—C—OH

H—C—OH

C—OH=O

meso-Tartaric acid
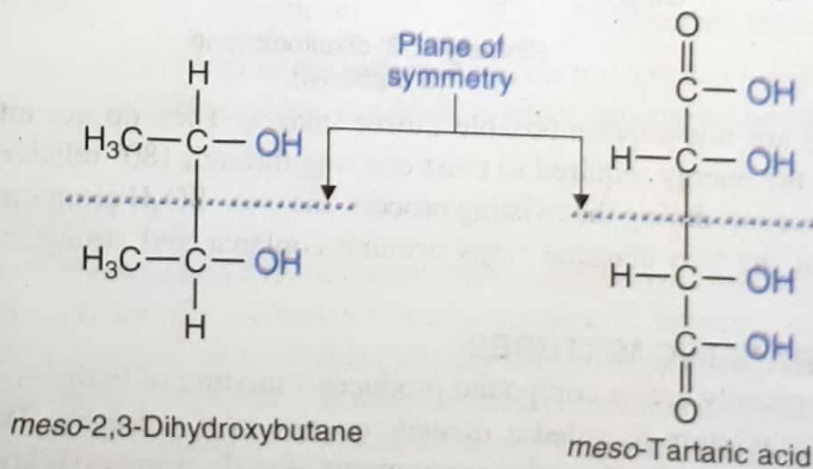
Fig. 7.11. Examples of meso compounds.

R,S SYSTEM OF SPECIFYING CONFIGURATIONS

The actual three-dimensional arrangement of groups in a chiral molecule is called its **Absolute Configuration**. We can specify the configuration by using the **R,S System**. The R,S system is also called the **Cahn-Ingold-Prelog System** (named after its inventors).

In the R,S system, we arrange the four groups attached to the chiral carbon in decreasing order of priority (1, 2, 3, 4) by applying the rules given below. We then view the chiral center with the lowest priority group (4) on the side opposite the observer (group priorities are shown in parentheses) :

Anticlockwise = S
As seen by the observer

Left turn = S
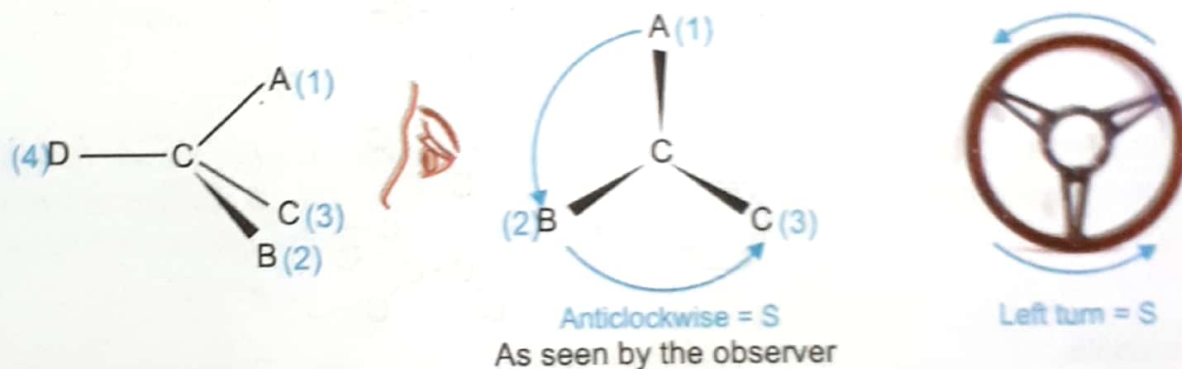
In the above example, A has the highest priority (1) ; B has the next highest (2) ; C has the next (3) ; and D has the lowest priority (4). We now go from high to low priority (1→2→3). To do so we move in an *anticlockwise* direction, and therefore we assign to this structure the **S Configuration** (S = *sinister* = left). In the structure given below, we go from highest to lowest priority by moving in a *clockwise* direction. We therefore assign to this structure the **R Configuration** (R = *rectus* = right).

Clockwise = R
As seen by the observer

Right turn = R
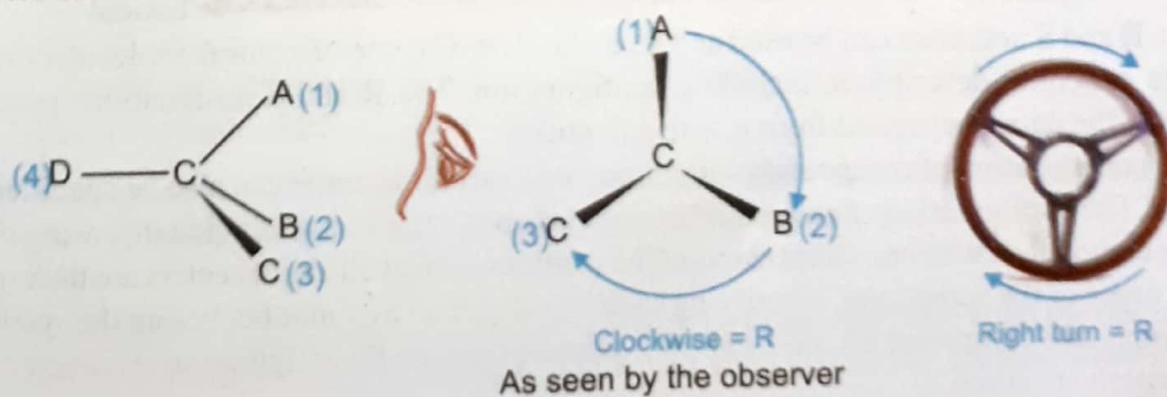
To establish the *group priorities* we use the following **Sequence Rules :**

Rule 1. Of the atoms attached directly to the chiral carbon atom, the one with the highest atomic number has the highest priority. For example,

$$I > Br > Cl > F > O > N > C > H$$
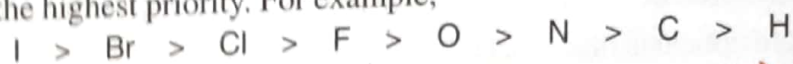
Highest ➞ Lowest

Rule 2. If the atoms attached to the chiral carbon atom are the same, we determine priority by going to the next atom away from the chiral carbon atom. For example,

$$\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{CH_3-C-}} > \underset{}{\overset{\overset{CH_3}{|}}{CH_3-CH-}} > CH_3CH_2- > CH_3-$$
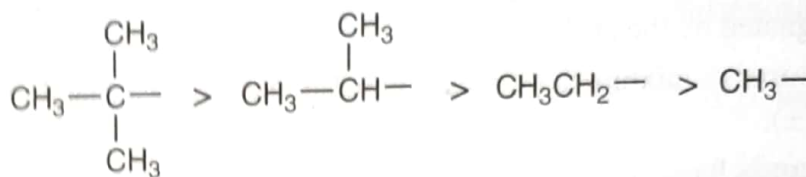
Highest ➞ Lowest

Ethyl has a higher priority than methyl because the ethyl group has (CHH attached to the first carbon, whereas the methyl carbon has only hydrogens (HHH), and C has priority over H. Isopropyl is of higher priority than ethyl because it has two carbons attached to the first carbon and ethyl has only one. If there is no difference at the second atom in the chain, we go to the next atom and so forth.

Rule 3. A double bond is treated as though each atom of the double bond were bonded to two atoms:

$$\overset{H}{\underset{H}{>}}C=C\overset{H}{<} \quad = \quad H-\overset{\overset{H}{|}}{\underset{\underset{C}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{C}{|}}{C}}-$$

$$H-C\equiv C- \quad = \quad H-\overset{\overset{C}{|}}{\underset{\underset{C}{|}}{C}}-\overset{\overset{C}{|}}{\underset{\underset{C}{|}}{C}}-$$

For example,

$$\bigcirc > HC\equiv C- > \underset{\underset{CH_2}{|}}{\overset{\overset{CH_3}{|}}{CH_3-C-}} > CH_2=CH- > \overset{\overset{CH_3}{|}}{CH_3-CH-} > CH_3CH_2-$$
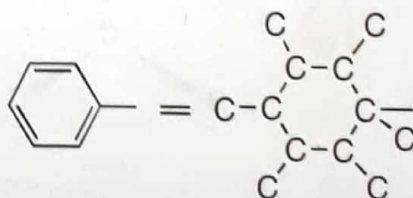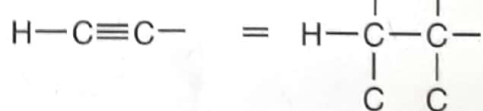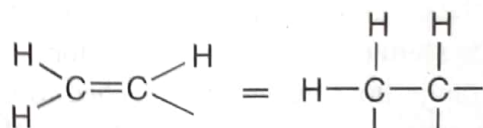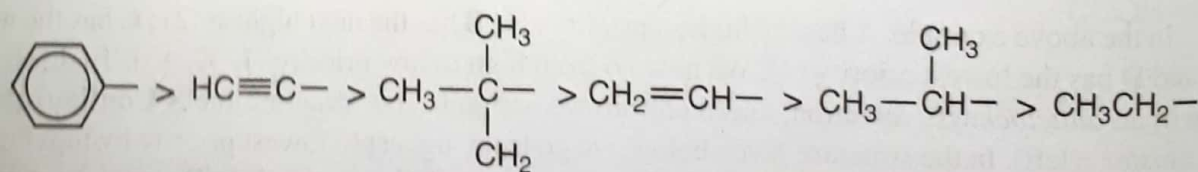
Highest ➞ Lowest

The **R** and **S** notations can be used as part of the IUPAC name of a chiral molecule, to provide a complete structural description, including configuration. The **R** and **S** designations precede the remainder of the name, separated from it with a hyphen.

The configuration of compounds with more than one chiral center can also be specified by the R,S system. The configuration of each chiral center carbon is determined individually, using the same rules as for compounds with one chiral carbon. The configuration of all chiral centers are then specified before the name of the compound, identifying each chiral carbon by a number before the symbol **R** or **S**. For example, the compound 2R,3S-3-chloro-2-pentanol has the **R** configuration at carbon 2 and the **S** configuration at carbon 3.

Points to Remember

1. Most errors in designating the configurations of molecules by R,S system come from a failure to point the lowest priority group away from the observer. You can easily assign the wrong configuration to a molecule if you do not point the lowest priority group away from yourself.

2. The priority sequence for the most common atoms and groups is as follows :

$$\text{(High Priority)} \quad -I, \ -Br, \ -Cl, \ -SH, \ -F, \ -O-\overset{\overset{\displaystyle O}{\|}}{C}-R, \ -OR, \ -OH, \ -NO_2,$$

$$-NH-\overset{\overset{\displaystyle O}{\|}}{C}-R, \ -NR_2, \ -NHR, \ -NH_2, \ -CCl_3, \ -\overset{\overset{\displaystyle O}{\|}}{C}-Cl, \ -\overset{\overset{\displaystyle O}{\|}}{C}-OR, \ -\overset{\overset{\displaystyle O}{\|}}{C}-OH,$$

$$-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2, \ -\overset{\overset{\displaystyle O}{\|}}{C}-R, \ -\overset{\overset{\displaystyle O}{\|}}{C}-H, \ -CN, \ -CH_2OH, \ C_6H_5-, \ -CR_3, \ -CHR_2, \ -CH_2R,$$

$$-CH_3, \ -H \ \text{(Low Priority)}$$
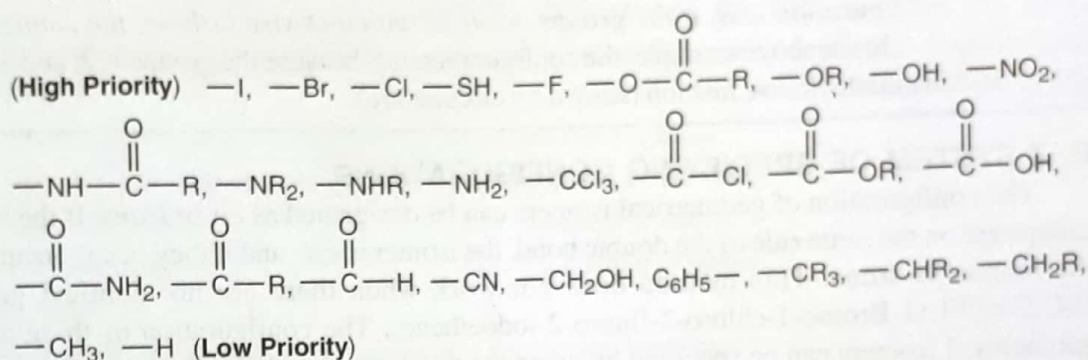
3. The Fischer projection formula is commonly used to show configuration without going to the trouble of drawing three-dimensional structure. In this convention the chiral center and the bonds to it are represented by crossed vertical and horizontal lines. It is understood that **groups attached by vertical bonds point away from the observer ; those bonded horizontally point toward the observer.** Some chemists show chiral carbon also.

Fischer Projection Formula
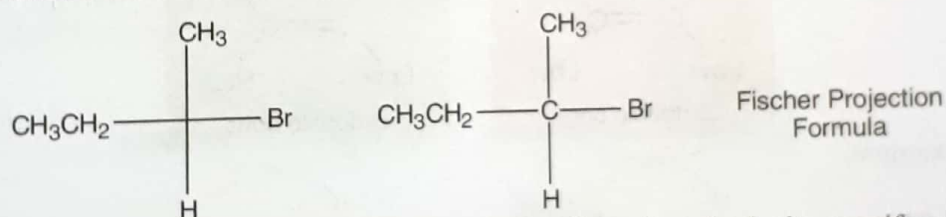
4. In exam you are ordinarily given a Fischer projection formula and asked to specify configuration using the symbols **R** and **S**. It is easy to do so if you follow the following *step-by-step* method. Consider the following example :

$\equiv$ S Configuration (Anticlockwise)
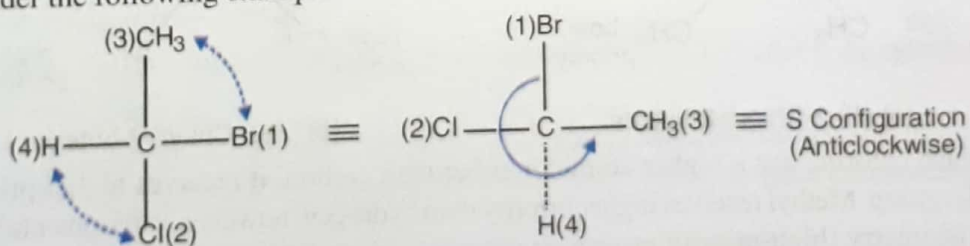
Order of Priority
(1) Br (atomic number 79.9) (*Highest*)
(2) Cl (atomic number 35.5)
(3) CH₃ (C, atomic number 12)
(4) H (atomic number 1) (*Lowest*)

Step 1. Determine the priority of groups attached to the chiral carbon atom. Apply the sequence rules carefully. In the above example, the order of priority is :

$$Br \ > \ Cl \ > \ CH_3 \ > \ H$$

Step 2. Position the lowest priority group (in this case H) down and away from the observer. This is done by interchanging groups bonded to the asymmetric carbon. *Remember that interchanging any pair of groups in a Fischer projection inverts the configuration.*

Interchanging two pairs of groups retains the original configuration. Thus, the interchange operation must always be done in pairs to avoid a configuration change.

In the above example, a dotted line has been used to highlight a bond between the chiral carbon and the lowest priority group (H). The interchange operations have been shown by dotted double-headed curved arrows.

Step 3. Specify the direction of decreasing priority of the three groups (1→2→3). Ignore the lowest priority group. *If the groups 1, 2, and 3 are arranged in clockwise fashion, the configuration is R. If the groups occur in anticlockwise fashion, the configuration is S.*

In the above example, the configuration is **S** because the groups 1, 2, and 3 are arranged in anticlockwise fashion (shown by circular arc).

E, Z SYSTEM OF SPECIFYING CONFIGURATIONS

The configuration of geometrical isomers can be designated as *cis* or *trans*. If the two identical groups are on the same side of the double bond, the isomer is *cis*; and if they occur on opposite sides, the isomer is *trans*. This method does not work when there are no identical groups, as in $BrClC=CFI$ (1-Bromo-1-chloro-2-fluoro-2-iodoethene). The configuration of these and all other geometrical isomers can be specified by using the notations **Z** and **E**. To do this, first determine the group of highest priority on each carbon. If the two high-priority groups are together on the same side, the configuration is **Z** (German, *zusammen* = together). If they are on opposite sides, the configuration is **E** (German, *entgegen* = opposite).

Z double bond

E double bond
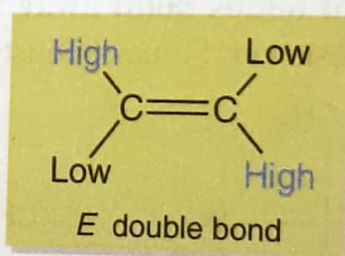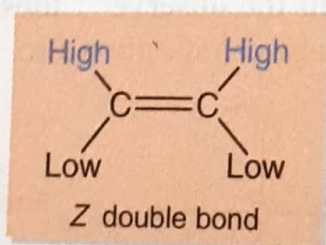
For example,
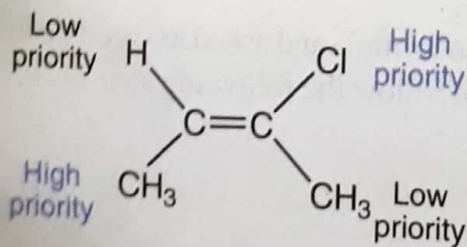
(a) (E)-2-Chloro-2-butene
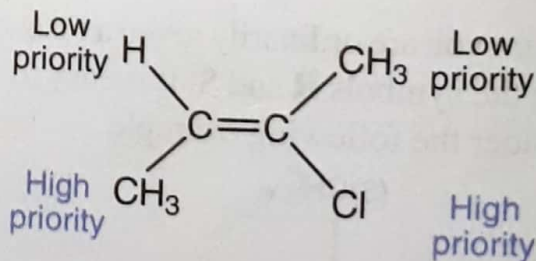
(b) (Z)-2-Chloro-2-butene

Because chlorine has a higher atomic number than carbon, it receives higher priority than a methyl (CH_3) group. Methyl receives higher priority than hydrogen, however, and isomer (a) is therefore assigned E geometry (high-priority groups on opposite sides of the double bond). Isomer (b) has Z geometry (high-priority groups on "zed zame zide" of the double bond).

Optical isomerism

➢ **Describe *optical isomers* as non-superimposable mirror images about an organic chiral centre.**

➢ **Identify chiral centres in a molecule of given structural formula.**

➢ **Explain that optical isomerism and *E/Z* isomerism are types of stereoisomerism**

E and Z isomers of but-2-ene
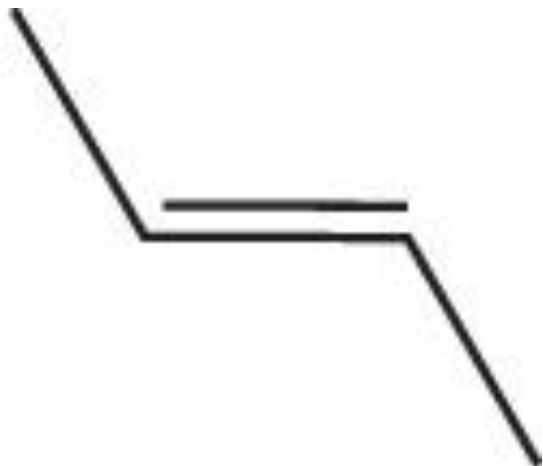
E-but-2-ene

Z-but-2-ene

Stereoisomers are species with the same structural formula but with a different arrangement of the atoms in space.

E-Z isomerism?

How to tell if it exists
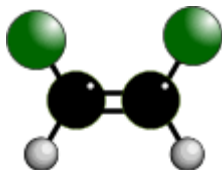
Two different atoms/groups attached   **Two different** atoms/groups attached   ✔   **GEOMETRICAL ISOMERISM**

Two similar atoms/groups attached   **Two similar** atoms/groups attached   ✘
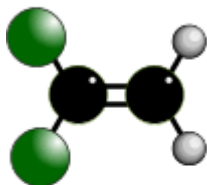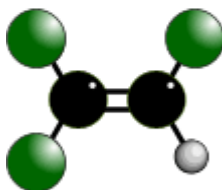
Two similar atoms/groups attached   **Two different** atoms/groups attached   ✘

Once you get two similar atoms/groups attached to one end of a C=C, you cannot have geometrical isomerism

Two different atoms/groups attached   **Two different** atoms/groups attached   ✔   **GEOMETRICAL ISOMERISM**
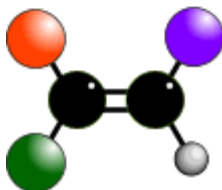
GEOMETRICAL ISOMERISM

RESTRICTED ROTATION OF C=C BONDS

C=C bonds have **restricted rotation** so the groups on either end of the bond are 'frozen' in one position; it isn't easy to flip between the two.
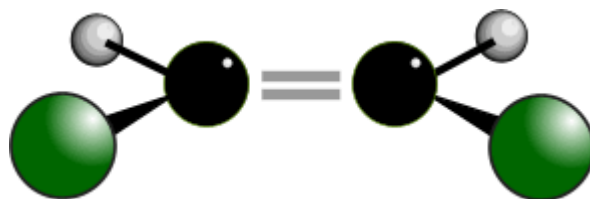
This produces **two possibilities**. The two structures cannot interchange easily so the atoms in the two molecules **occupy different positions in space**.
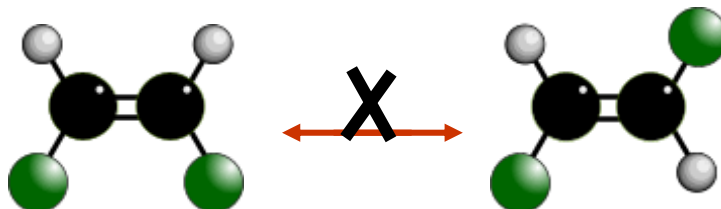
- For some molecules the mirror image is a different molecule (the mirror image is non-superimposable).
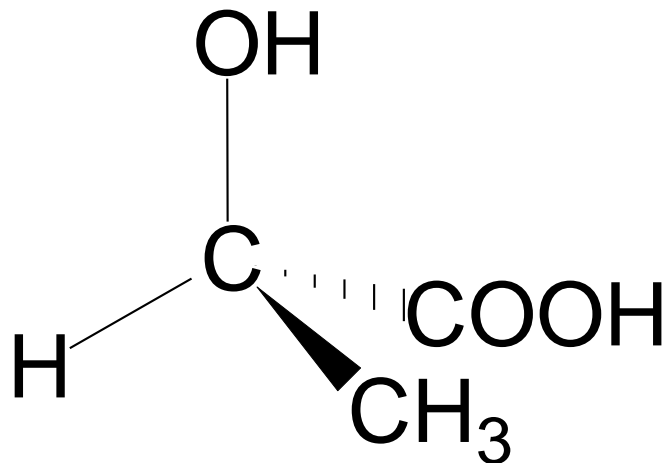
(-) lactic acid
in sour milk
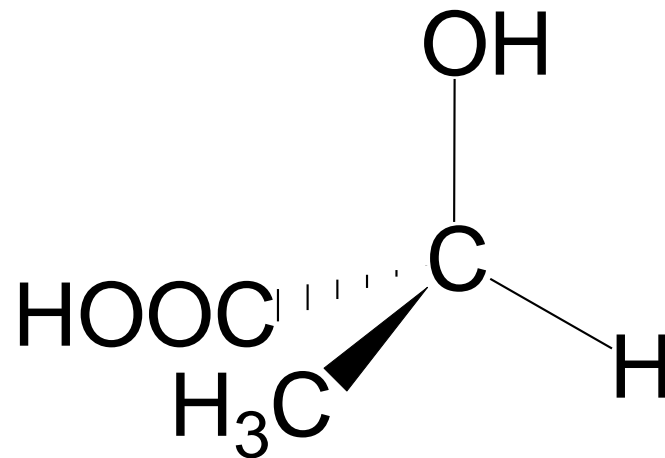
(+) lactic acid
in muscles

D-Alanine

L-Alanine

Mirror

COOH

C

CH₃

H

NH₂

CH₃

NH₂

COOH

C

H
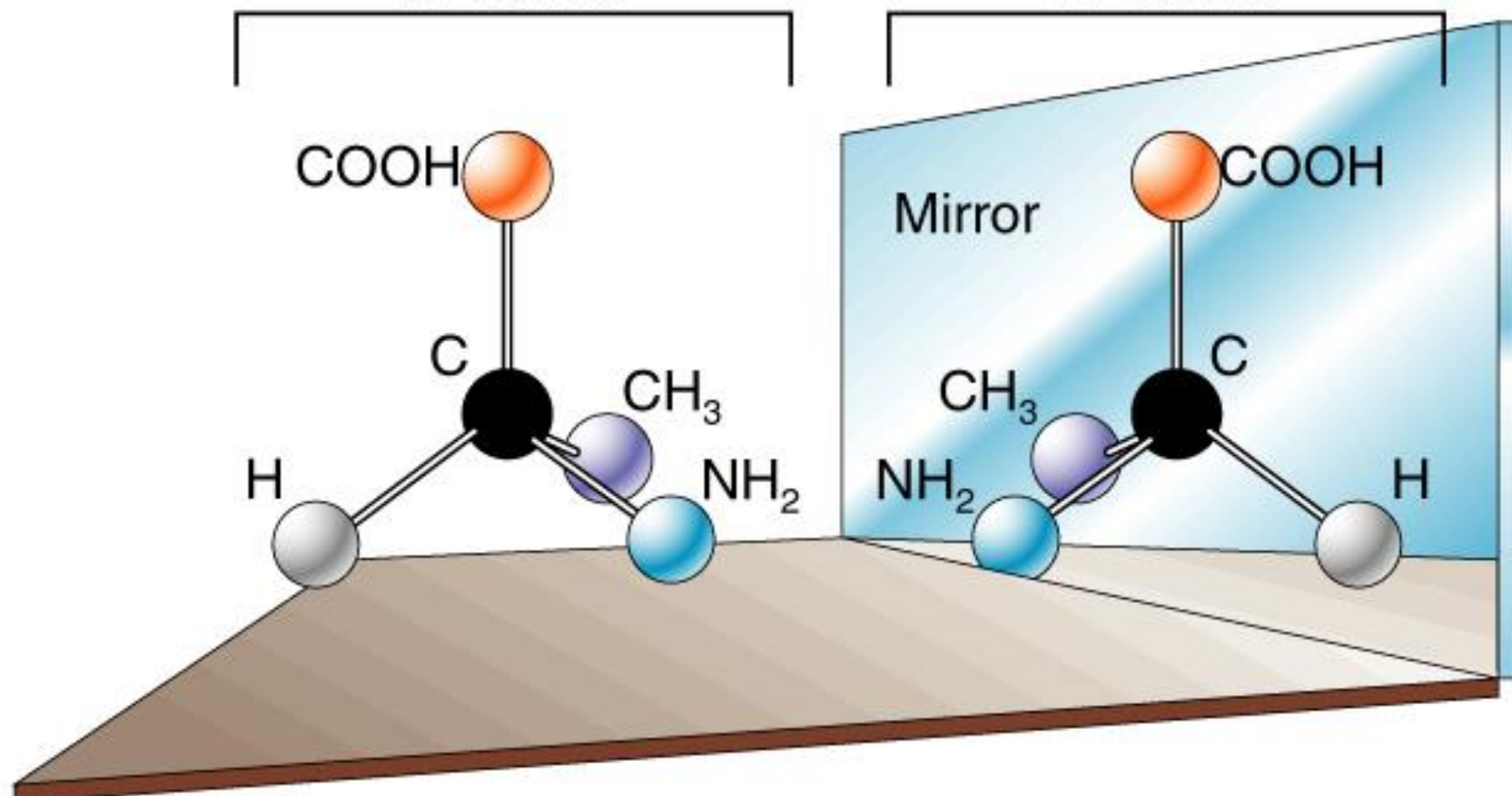
- Left and right hands are an example of non-superimposable mirror images.
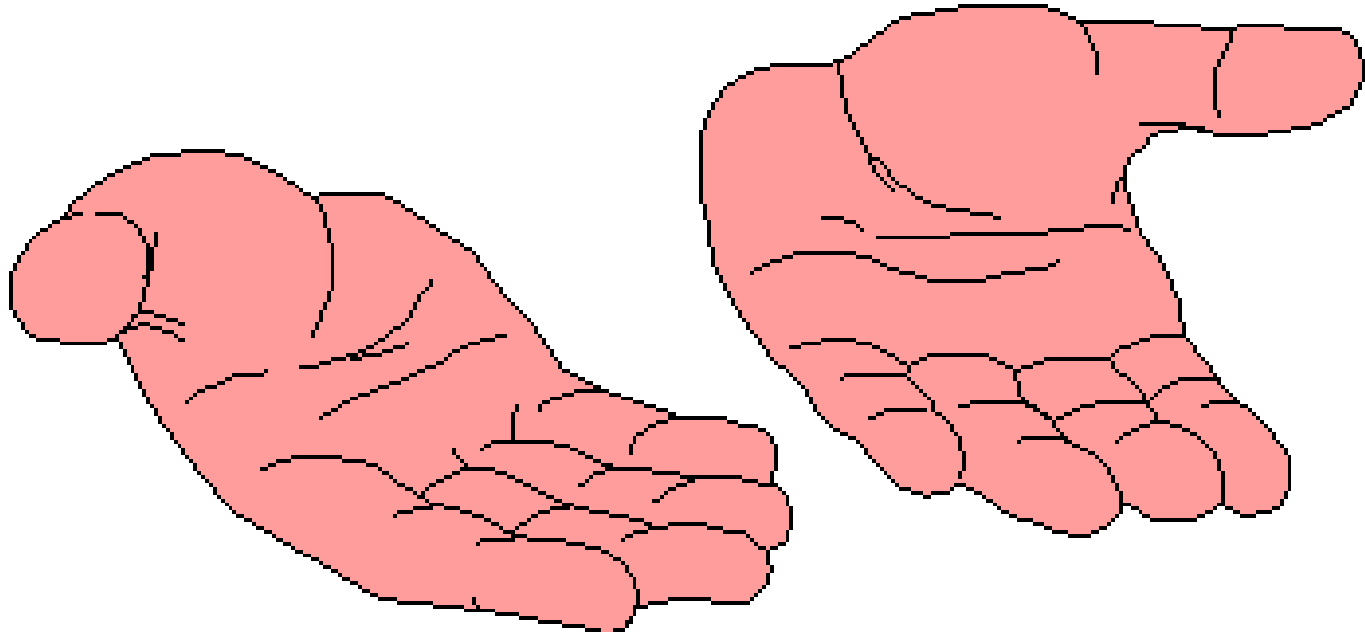
Optical isomers (or enantiomers) are stereoisiomers that are non-superimposable mirror images of each other.

D-Alanine

L-Alanine

Mirror

COOH

COOH

C

C

CH₃

CH₃

H

NH₂

NH₂

H
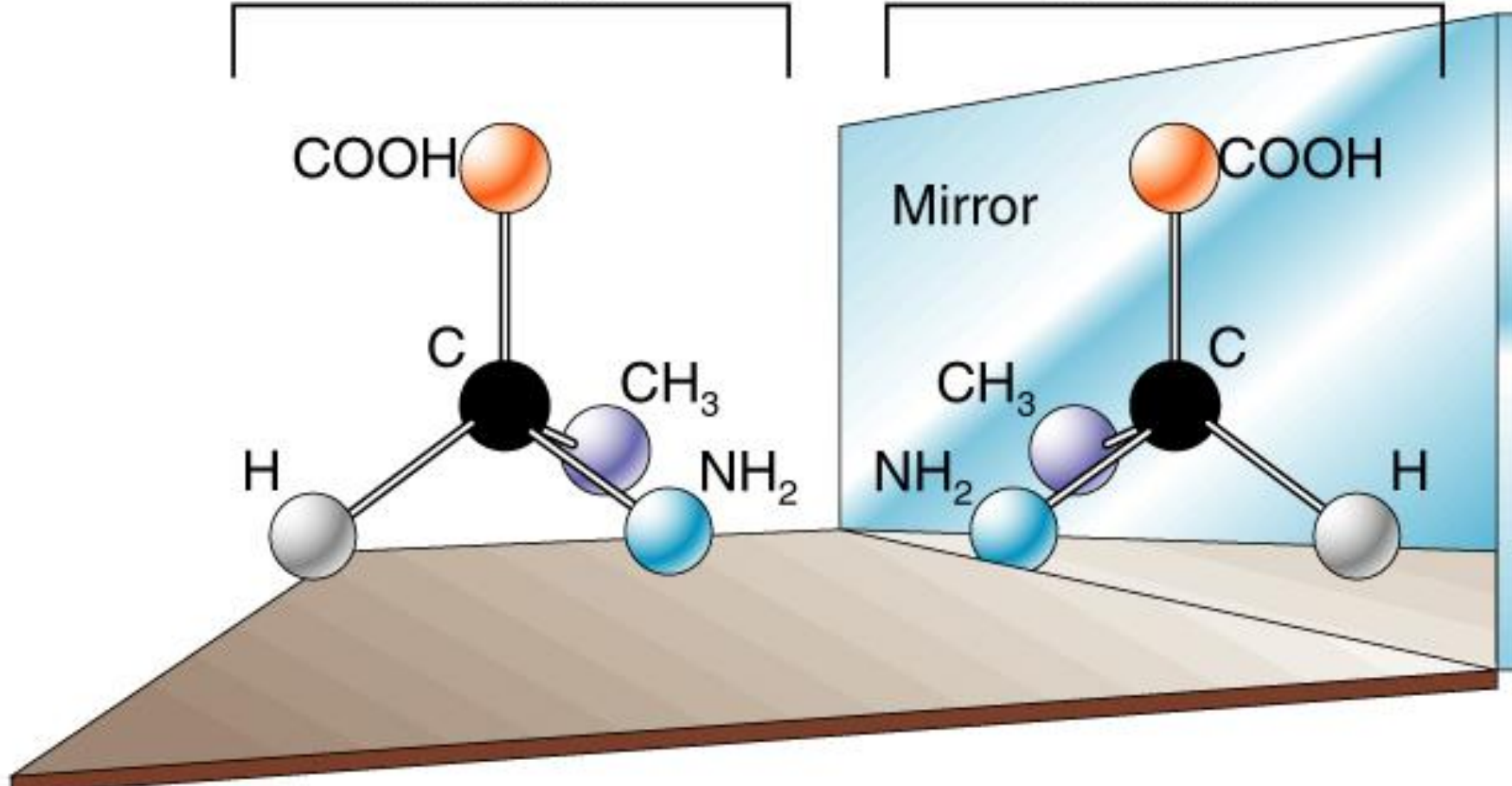
- **Optical isomerism arises in organic molecules that contain a chiral carbon.**
- **Chiral carbon: is a carbon atom attached to four different atoms or groups of atoms.**
- **Such molecules are said to be chiral or optically active.**
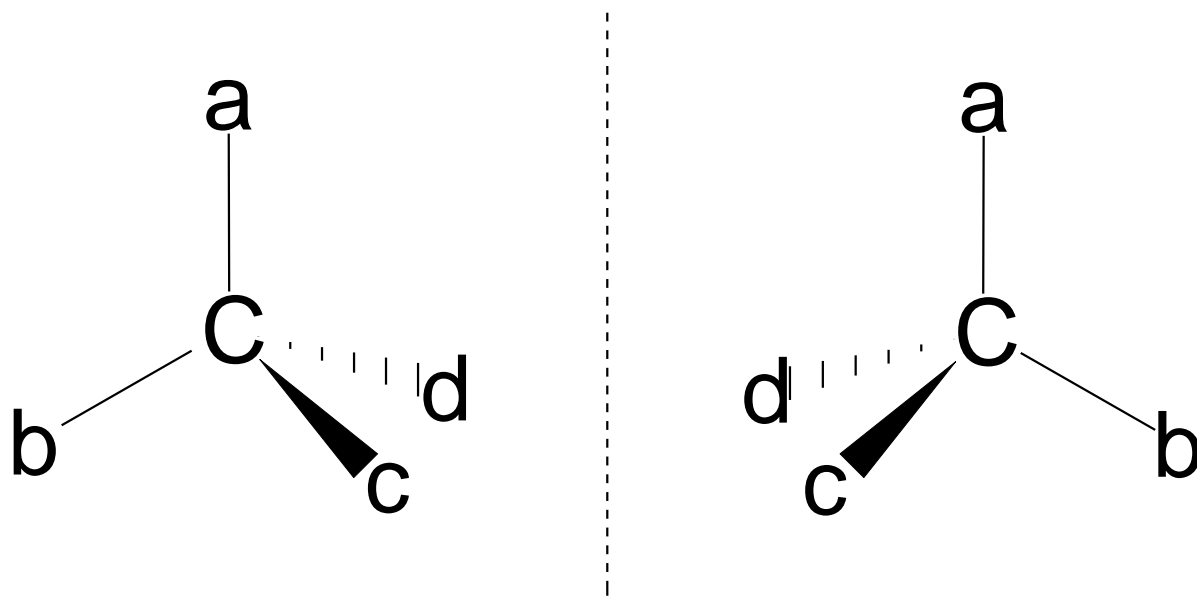
Optical isomers are said to be chiral, and the isomers are called a pair of enantiomers.

The carbon bonded to the four different groups is called the chiral centre or asymmetric carbon.

TASK   Which of the following molecules are optically active?

1) propan-2-ol
2) 2-chlorobutane
3) 1-chlorobutane
4) 3-methylhexane

5) butanone
6) 2-methylbutanoic acid
7) butan-2-ol
8) 1-chloro-3-methylpentane

propan-2-ol

$$CH_3 \text{---} CH \text{---} CH_3$$
$$|$$
$$OH$$
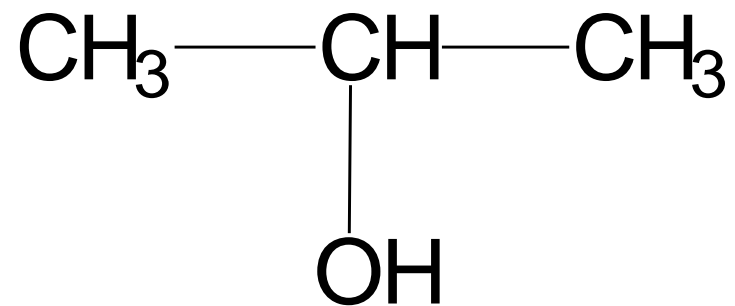
NOT OPTICALLY ACTIVE

2-chlorobutane

$$CH_3 \text{—} CH \text{—} CH_2 \text{—} CH_3$$
$$|$$
$$Cl$$
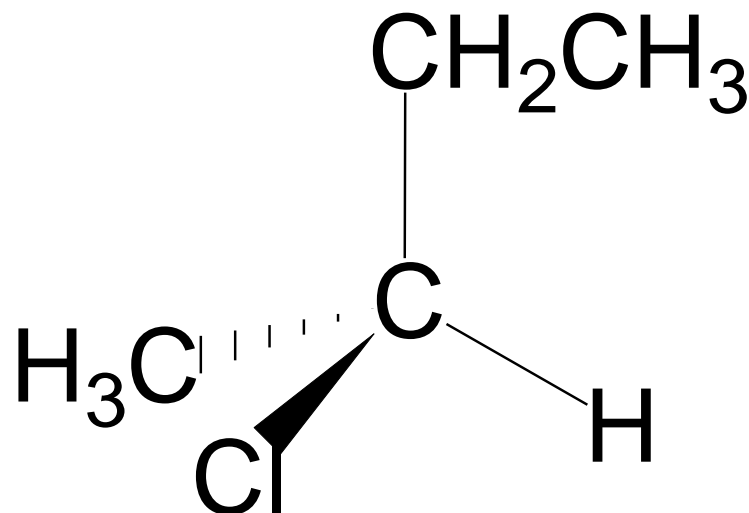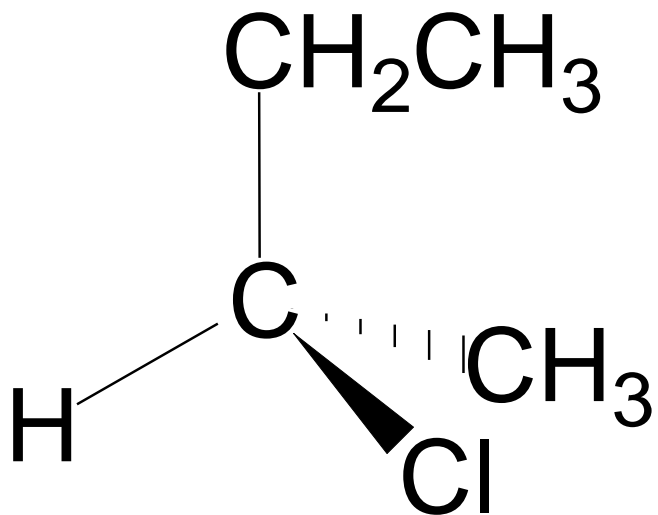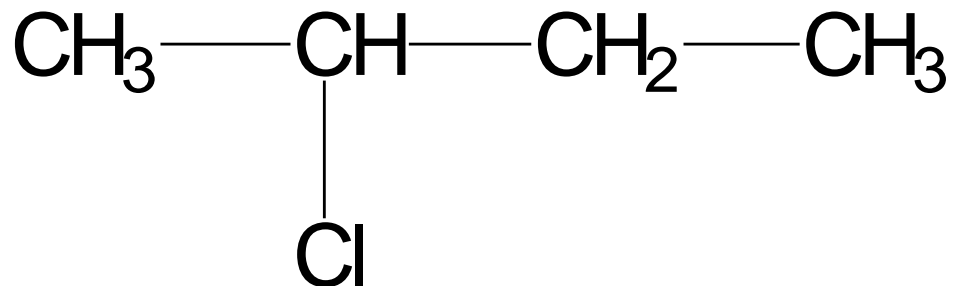
OPTICALLY ACTIVE

1-chlorobutane

$$CH_2 \text{—} CH_2 \text{—} CH_2 \text{—} CH_3$$
$$|$$
$$Cl$$
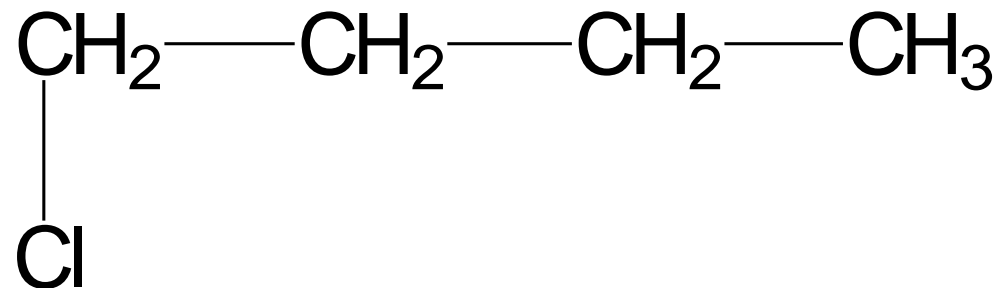
NOT OPTICALLY ACTIVE

3-methylhexane

$$CH_3 — CH_2 — CH — CH_2 — CH_2 — CH_3$$
$$|$$
$$CH_3$$
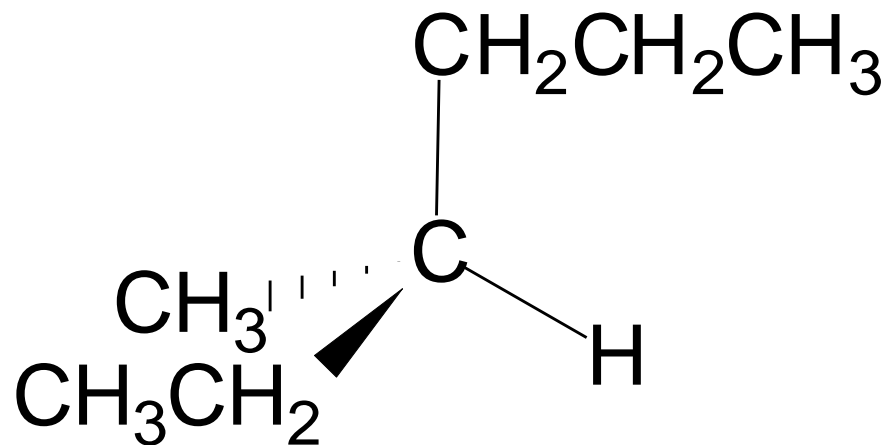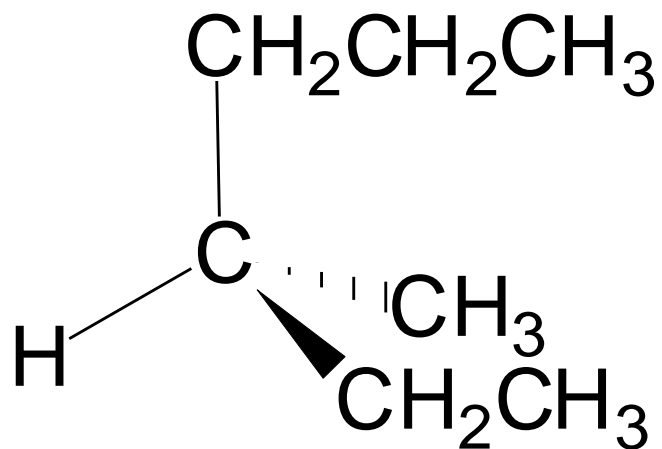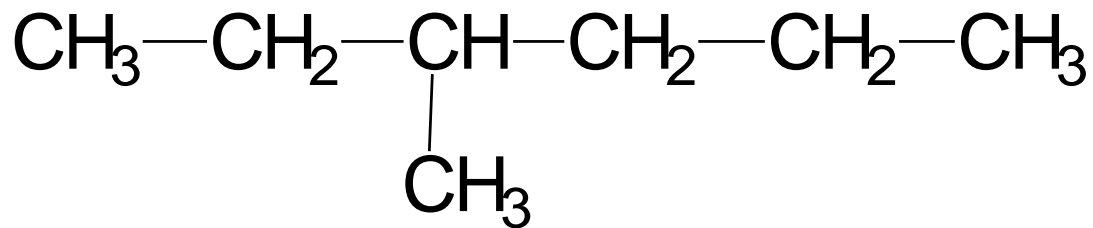
OPTICALLY ACTIVE

butanone

$$CH_3 - \overset{\overset{\displaystyle O}{\|}}{C} - CH_2 - CH_3$$
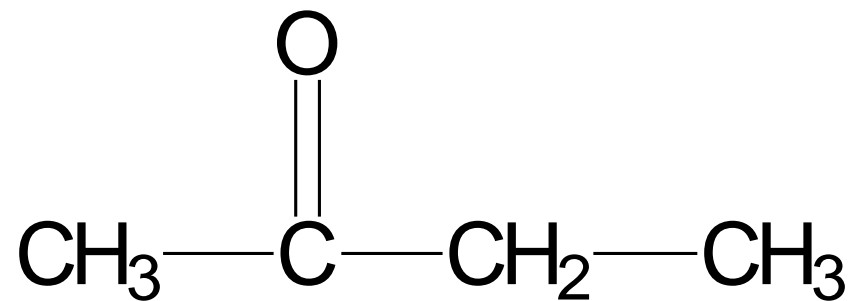
NOT OPTICALLY ACTIVE

propan-2-ol

$$CH_3 - CH - CH_3$$
$$|$$
$$OH$$
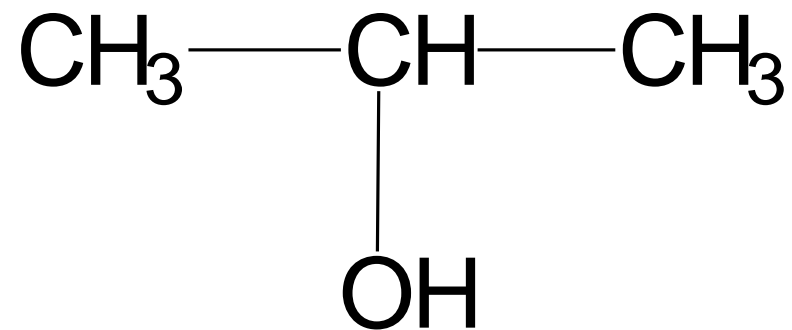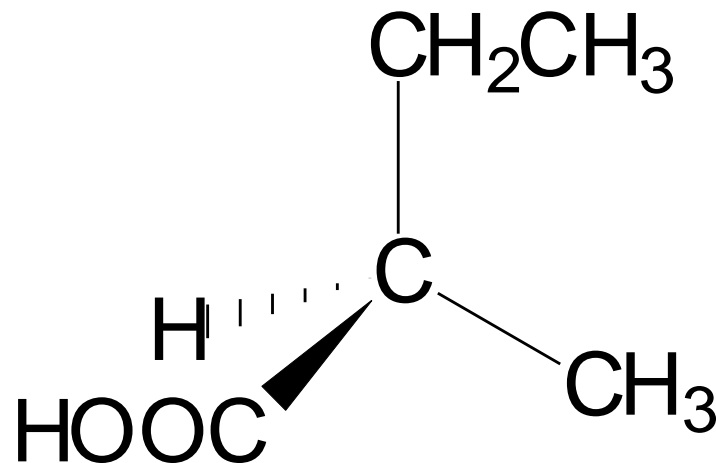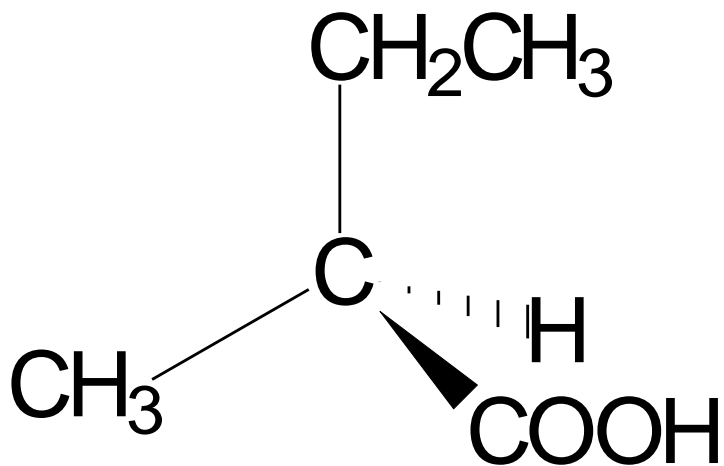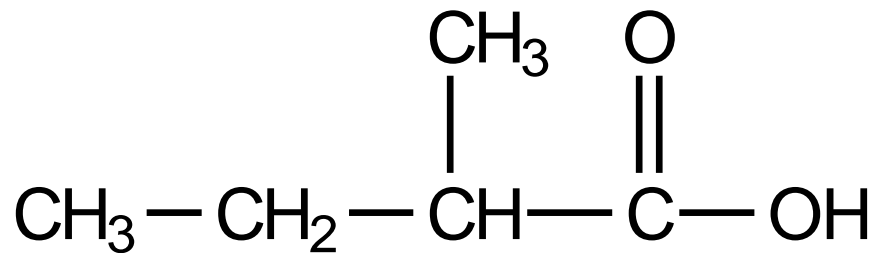
NOT OPTICALLY ACTIVE

butan-2-ol
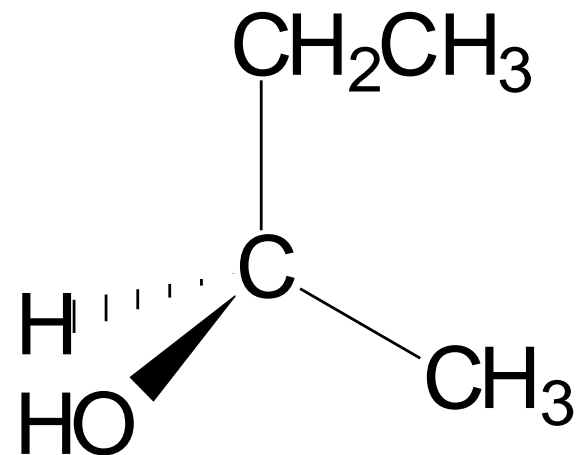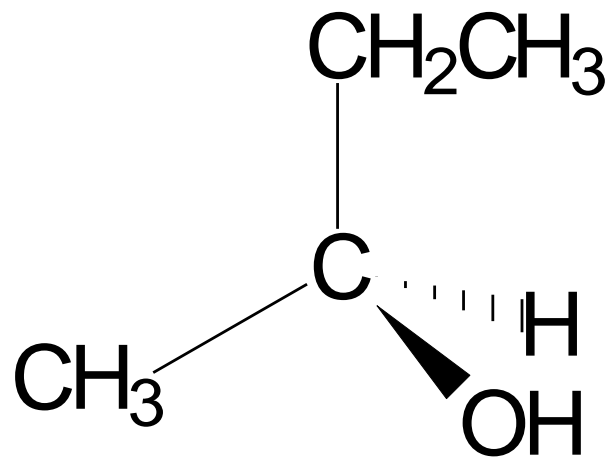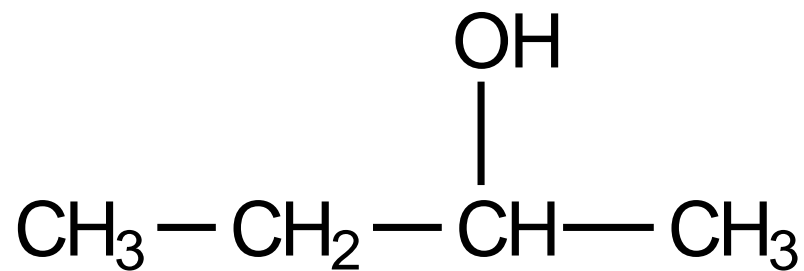
OPTICALLY ACTIVE

1-chloro-3-methylpentane

$$CH_3-CH_2-\underset{\underset{\displaystyle CH_3}{|}}{CH}-CH_2-CH_2-Cl$$
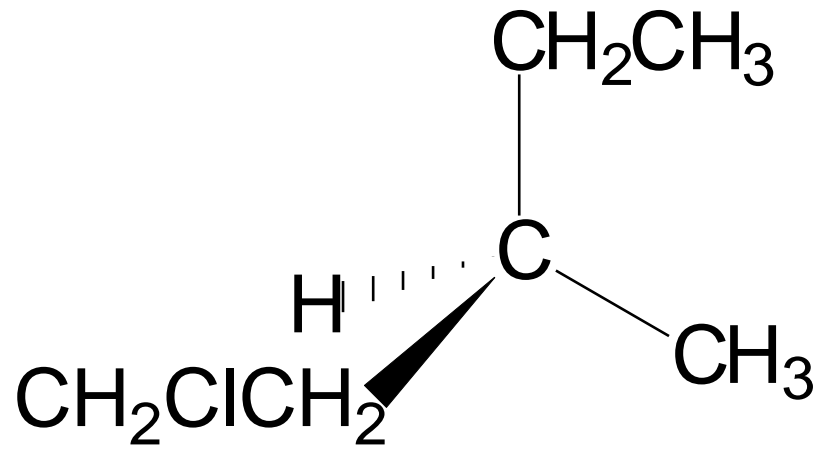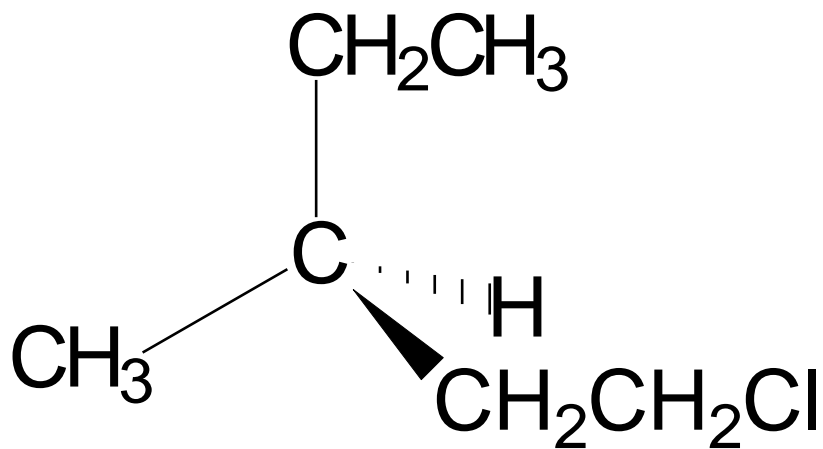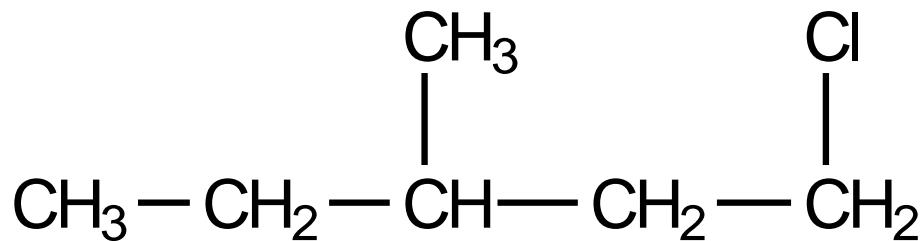
OPTICALLY ACTIVE

Identify the chiral carbon
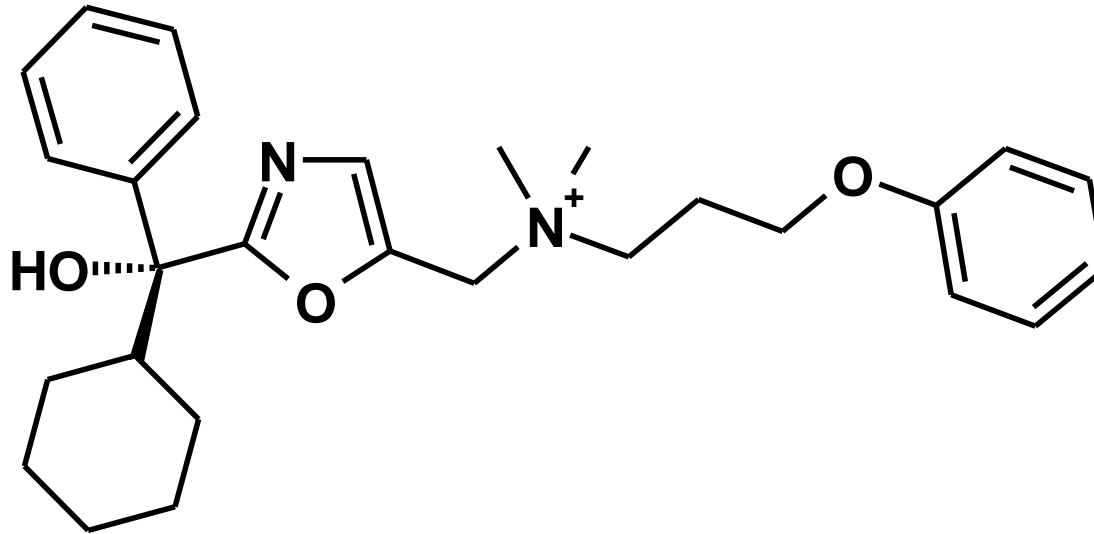
Very potent M3 antagonist.

Clinical candidate for COPD

- Molecules that are optical isomers are called enantiomers.

- Enantiomers have identical chemical and physical properties, except:

  - Their effect on plane polarised light;
  - Their reaction with other chiral molecules

- Light is a form of electromagnetic radiation.
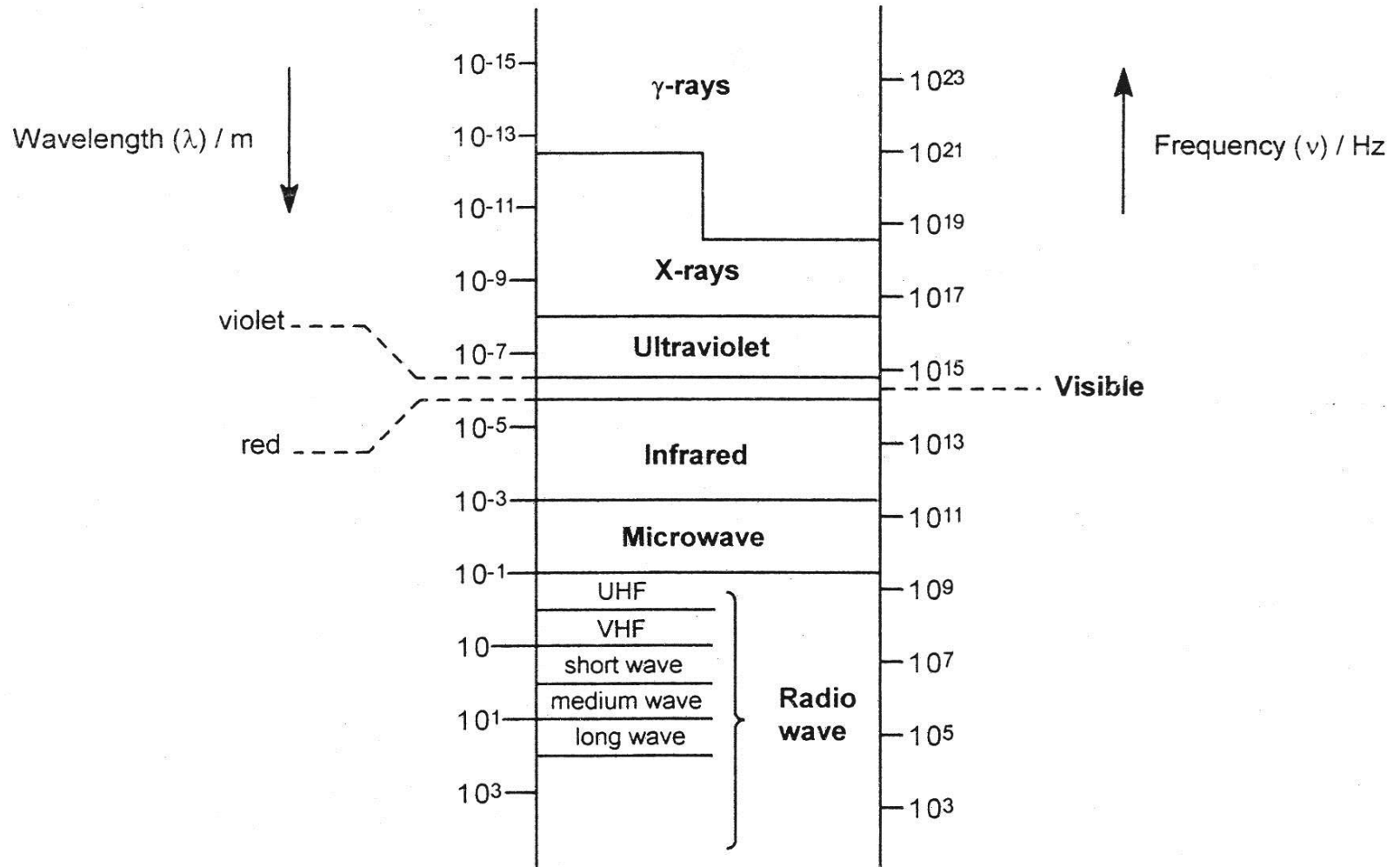
- The wave vibrations are perpendicular to the direction of travel of the wave.
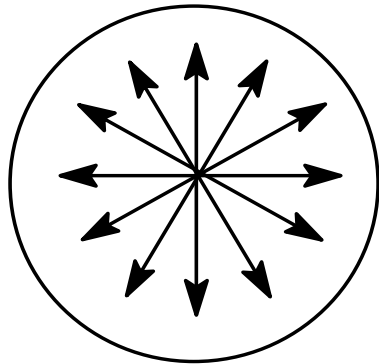
normal light
(waves vibrate in all directions)
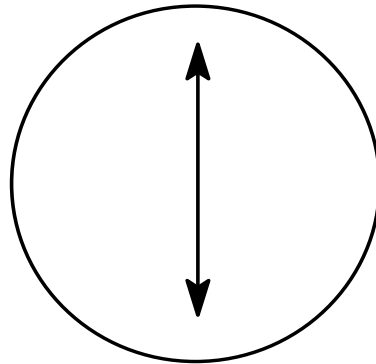
plane-polarised light
(vibrates in only one direction)
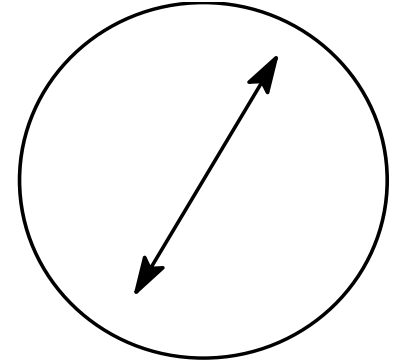
plane-polarised light after
clockwise rotation

- Optical isomers rotate the plane of plane polarised light.
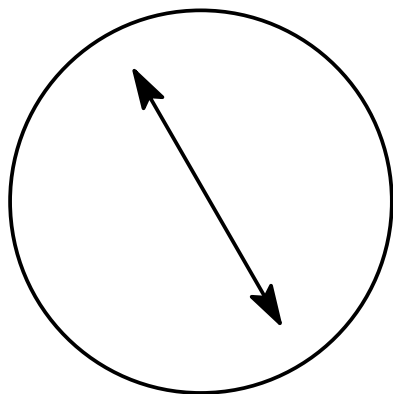
(-)-enantiomer
(anticlockwise rotation)
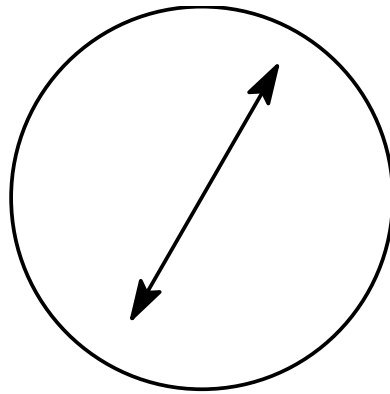
(+)-enantiomer
(clockwise rotation)
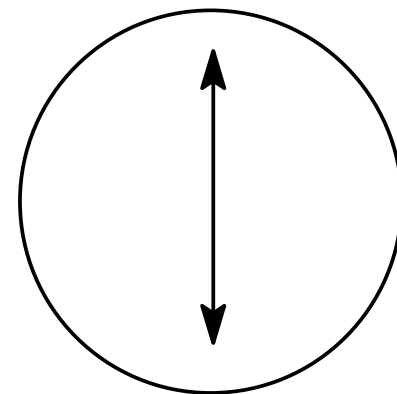
(±)-racemate
(no overall effect)

Emergent light
with rotated plane
of plarization

α

Nicol
prism
polarizer

Nicol
prism
analyzer

Incident
plane-polarized light

Polarimeter tube containing
solution of an optical isomer

Unpolarized
light
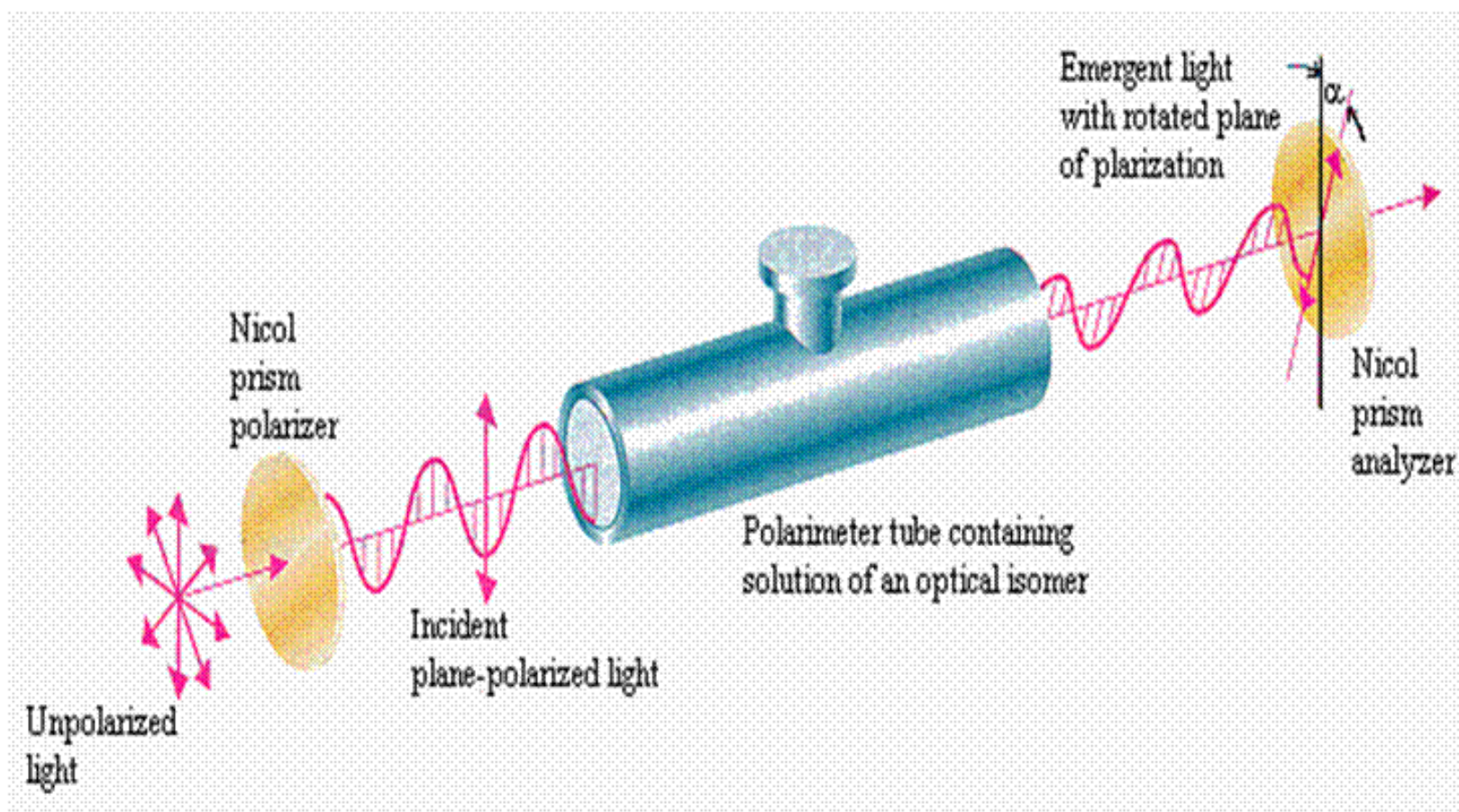
- Chiral molecules often react differently with other chiral molecules.

- This is like the idea that a right hand does not fit a left handed glove – the molecule must be the correct shape to fit the molecule it is reacting with.

- Many natural molecules are chiral and most natural reactions are affected by optical isomerism.

- For example, most amino acids (and so proteins) are chiral, along with many other molecules.

- In nature, only one optical isomer occurs (e.g. all natural amino acids are rotate polarised light to the left).

- Many drugs are optically active, with one enantiomer only having the beneficial effect.

- In the case of some drugs, the other enantiomer can even be harmful, e.g. thalidomide.

- In the 1960's thalidomide was given to pregnant women to reduce the effects of morning sickness.

- This led to many disabilities in babies and early deaths in many cases.
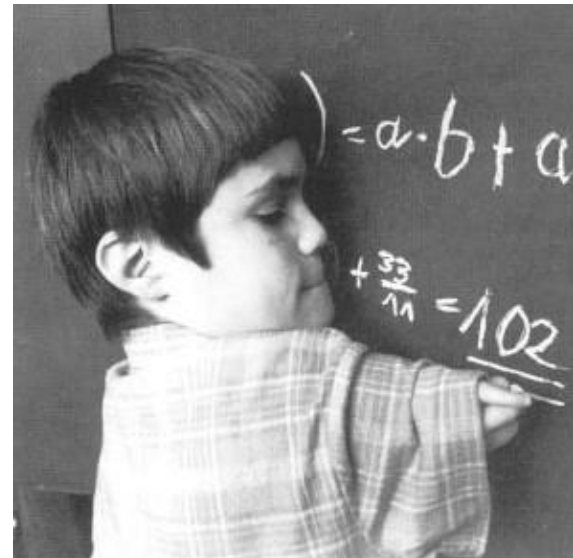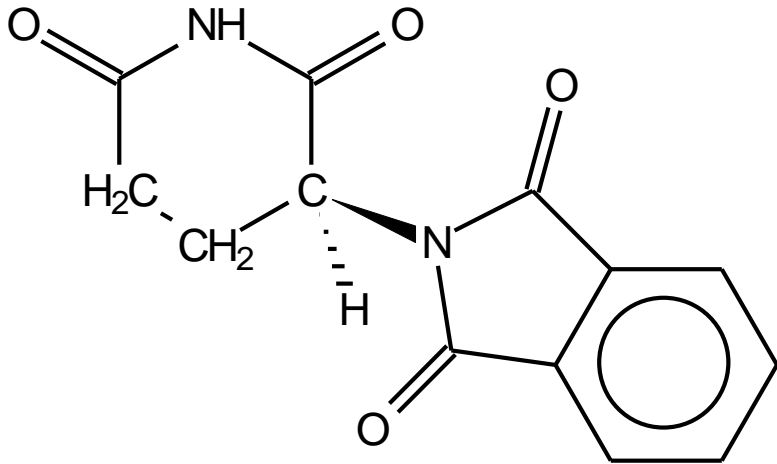
S thalidomide (effective drug)
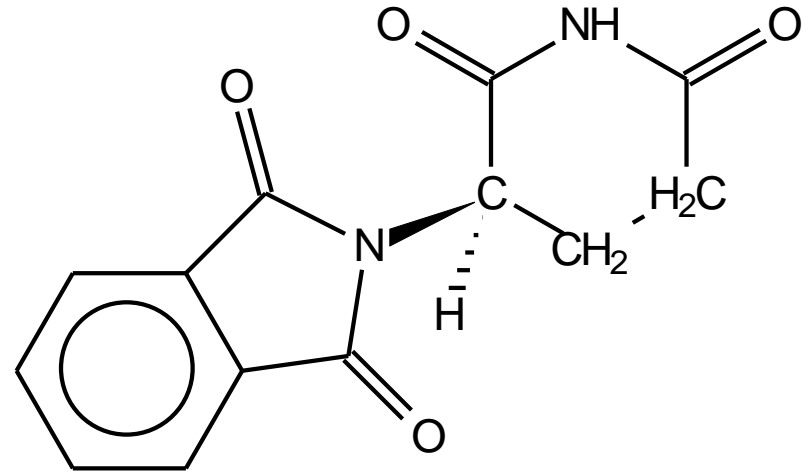
R thalidomide (dangerous drug)

The body racemises each enantiomer, so even pure S is dangerous as it converts to R in the body.

- Thalidomide was banned worldwide when the effects were discovered.

- However, it is starting to be used again to treat leprosy and HIV.

- Its use is restricted though and patients have to have a pregnancy test first (women!) and use two forms of contraception (if sexually active).
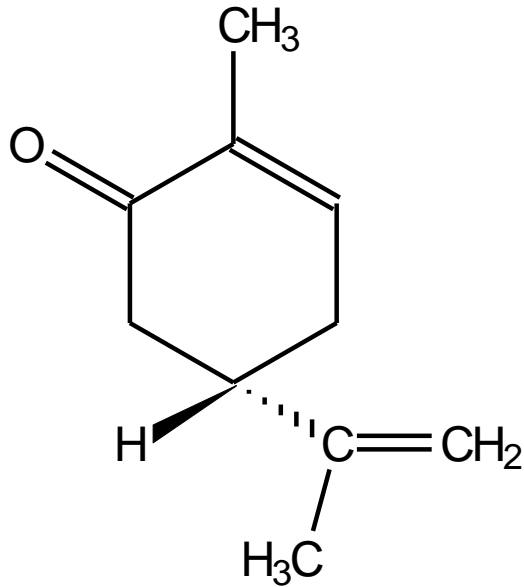
S carvone (caraway seed)

R carvone (spearmint)

Caraway Seed has a warm, pungent, slightly
bitter flavour with aniseed overtones.
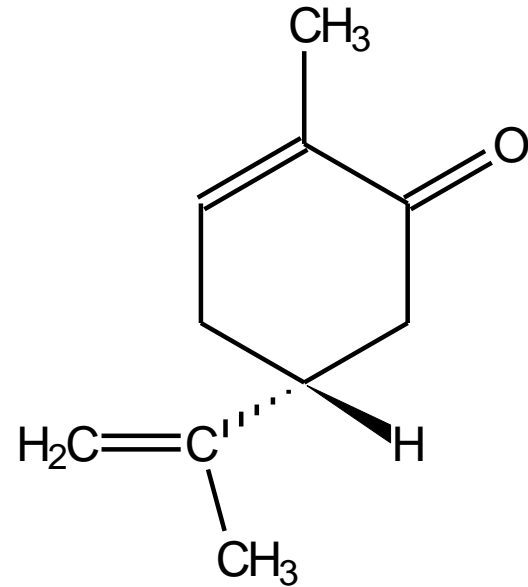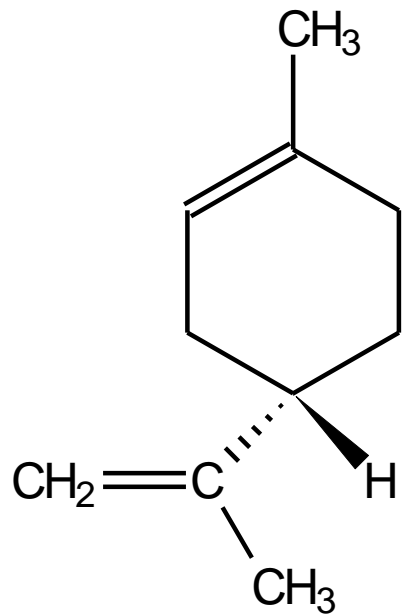
S limonene (lemons)
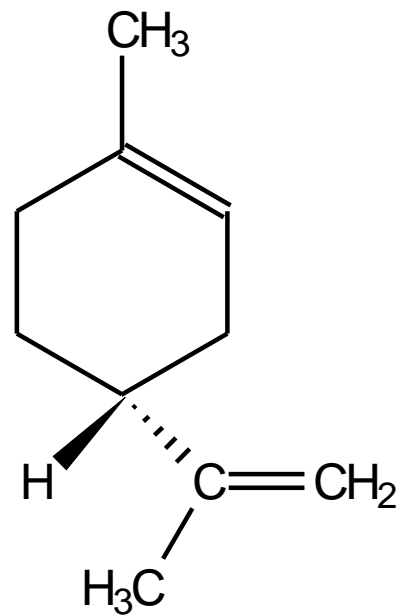
R limonene (oranges)

The butan-2-ol molecule has a chiral carbon
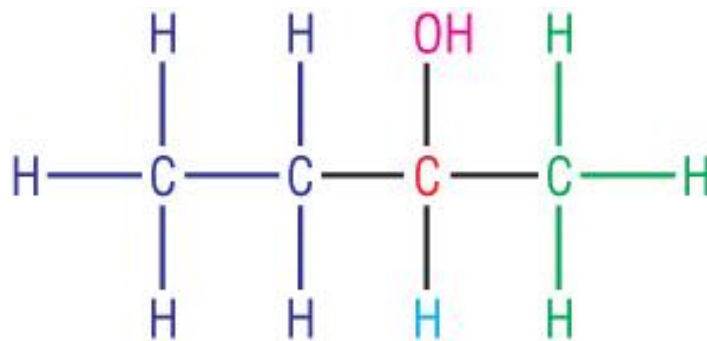
Optical isomers of CH$_3$CH$_2$CH(NH$_2$)CH$_3$

Mirror
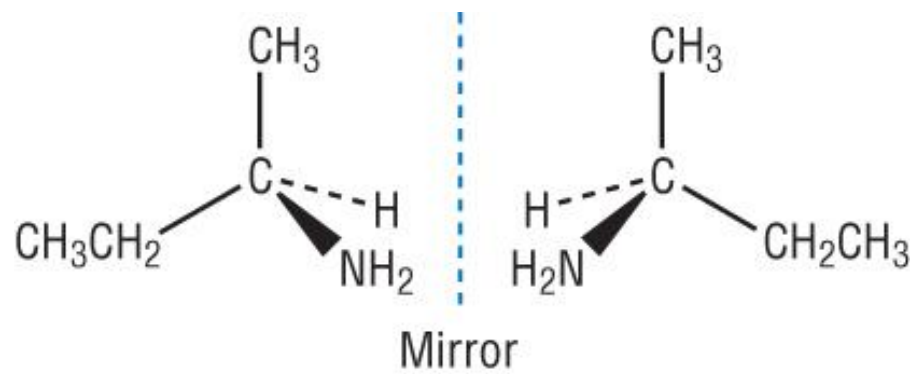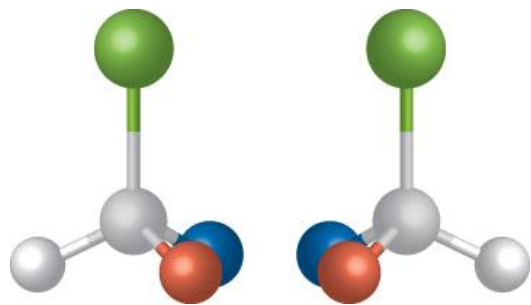
Spectroscopy Spectra 1

Introduction

- For synthesis of new compound we use "4" methods of spectral method to make identification for the structure of the compound.

➡ These four methods are:

- (**1**) Ultra Violet (U.V)   (**2**) Infrared (I.R)

- (**3**) Mass spectrometry (M.S)

- (**4**) Nuclear Magnetic Resonance (N.M.R)

Spectroscopy

The light is a beams of electromagnetic waves

Spectroscopy

- It is the branch of science that deals with the study of interaction of matter with light.

OR

- It is the branch of science that deals with the study of interaction of electromagnetic radiation with matter.

❖**<u>Idea</u>**:

•Compound which we want to identify absorb an energy with a certain wave length causes excitation and then it will emit this energy which pass to detector and pass to plotter to plot a chart.

.

•

UV-Vis spectroscopy
Electronic absorption spectroscopy

white
sunlight

window
shade

hole

glass prism

white
card

spectrum

red
orange
yellow
green
blue
indigo
violet
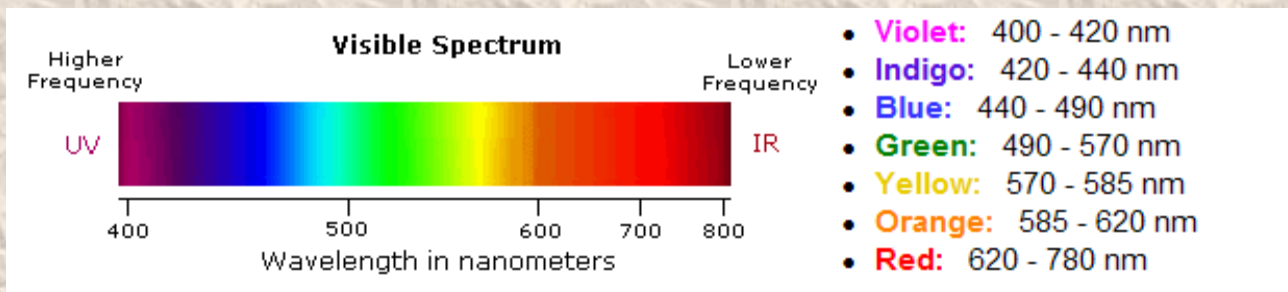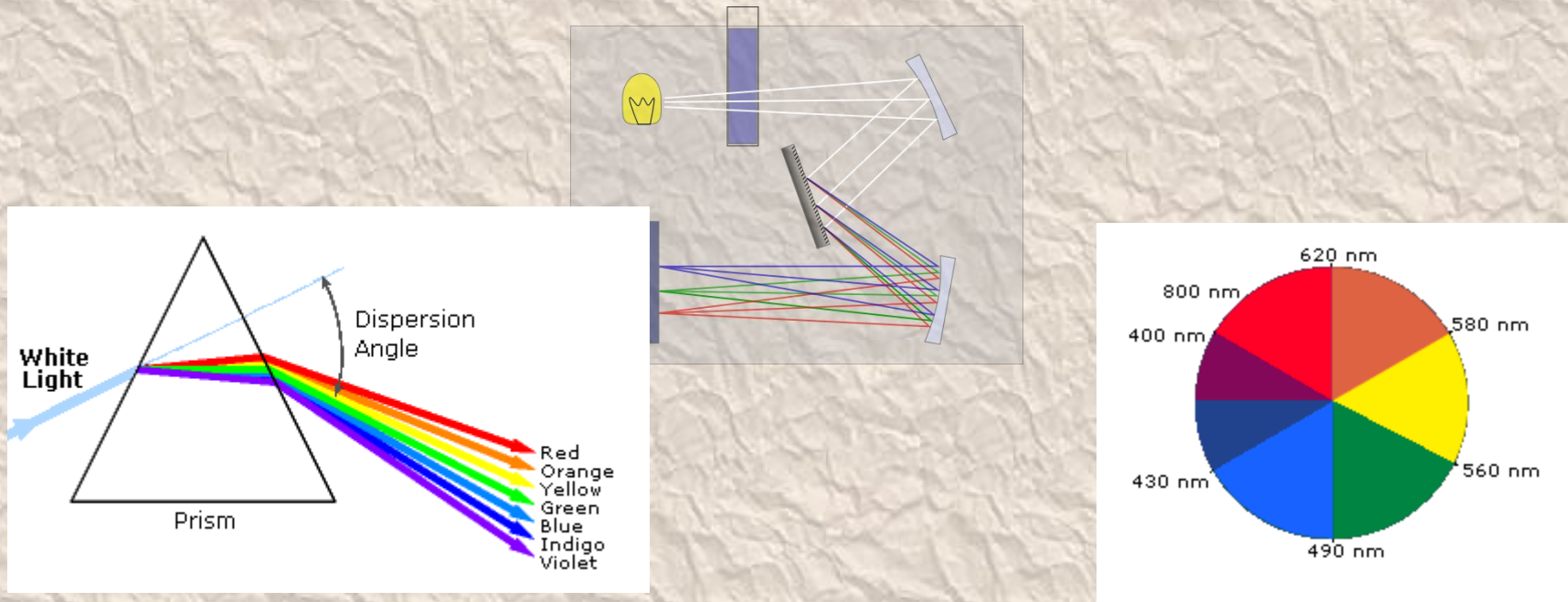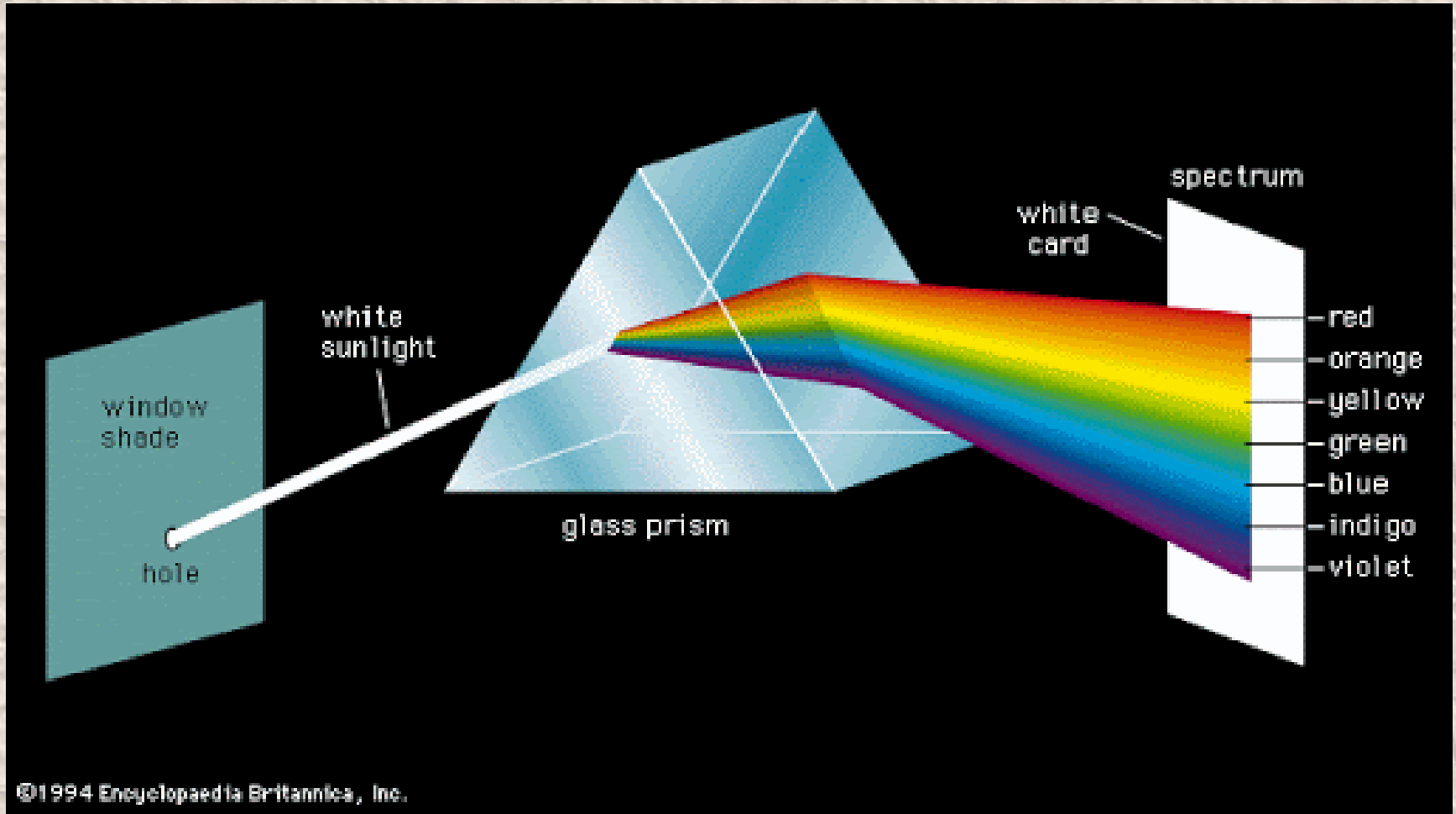
Electromagnetic Radiation
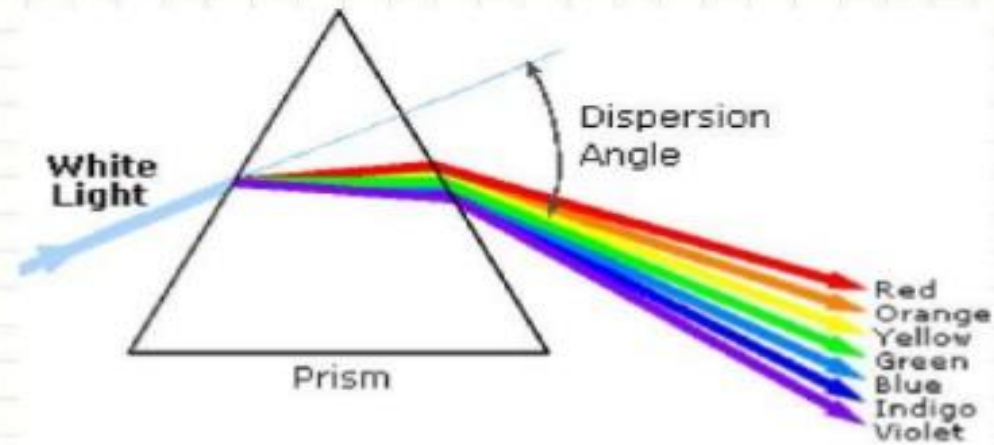
Violet	400 - 420 nm	Yellow	570 - 585 nm
Indigo	420 - 440 nm	Orange	585 - 620 nm
Blue	440 - 490 nm	Red	620 - 780 nm
Green	490 - 570 nm		

The Electromagnetic Spectrum
Wavelength in meters

Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma Ray
$\longleftarrow 1$	1 to 10^{-3}	10^{-3} to 10^{-6}	8×10^{-7} to 4×10^{-7}	3×10^{-7} to 10^{-8}	10^{-8} to 10^{-12}	$10^{-12} \longrightarrow$

About the size of:

Buildings	Grains of sugar	Protozoans	Bacteria	Molecules	Atoms	Atomic nuclei
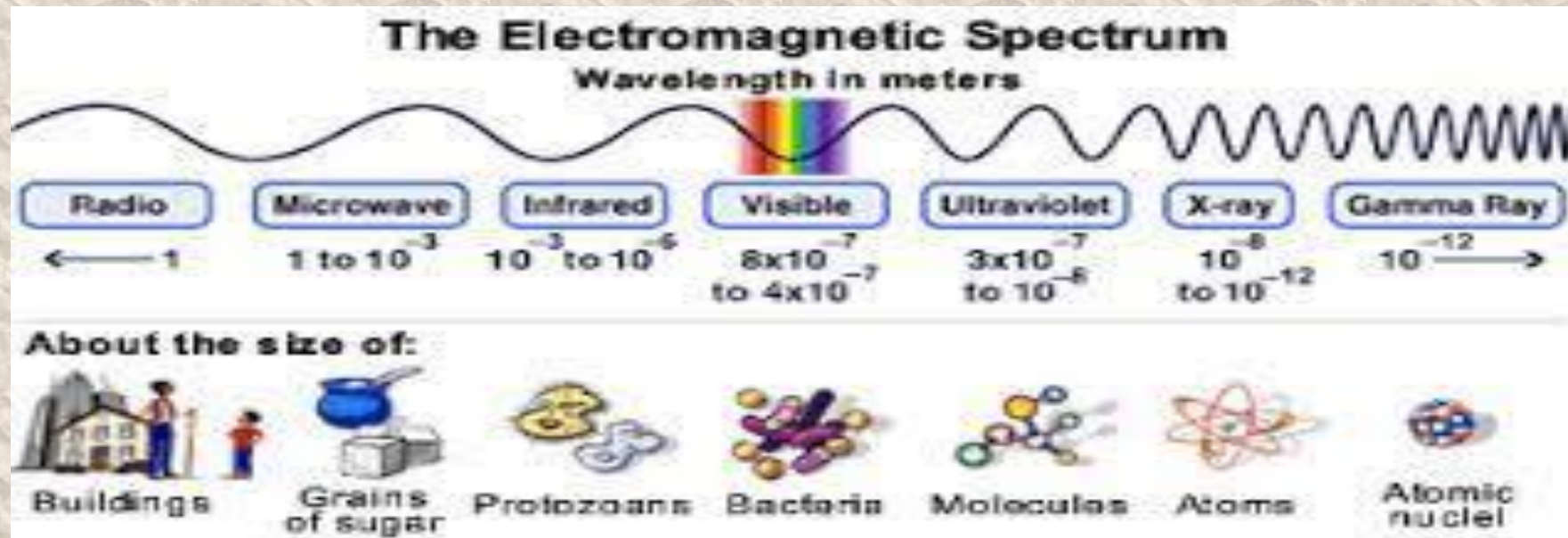
Spectroscopy
Regions of the Electromagnetic Spectrum

1. Many regions are defined as much by the mechanism of the transitions (e.g. outer shell electron) as by the frequency or energy of the transitions

Gamma rays	X-rays	UV + visible	Infrared	Microwaves	Radio waves

Short wavelengths — Outer shell electrons — Bond vibration — Nuclear spin — Long wavelengths

High Energies — Nuclear transitions — Inner shell electrons — Molecular rotations — Electron spin — Low Energies
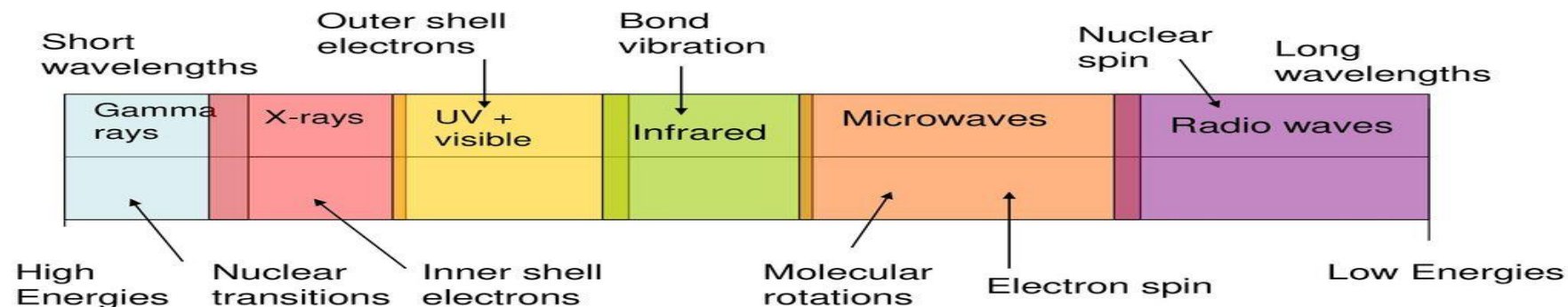
Principles of Spectroscopy

- The principle is based on the measurement of spectrum of a sample containing atoms / molecules.

- Spectrum is a graph of intensity of absorbed or emitted radiation by sample verses frequency (ν) or wavelength (λ).

- Spectrometer is an instrument design to measure the spectrum of a compound.

Electromagnetic Radiation
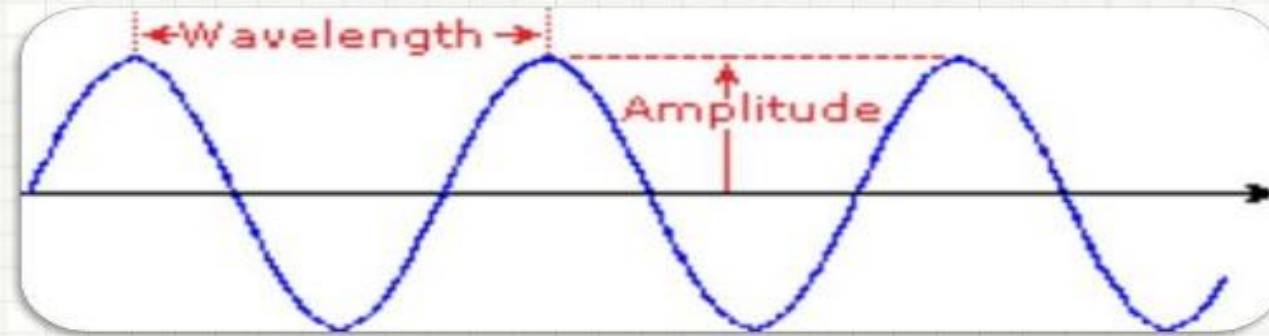
- The relationship between wavelength & frequency can be written as:

$$c = v\,\lambda$$

- As photon is subjected to energy, so

$$E = h\,v = h\,c\,/\,\lambda$$

$$E\;\alpha\;\lambda$$

Principles of Spectroscopy

1. Absorption Spectroscopy:

- An analytical technique which concerns with the measurement of absorption of electromagnetic radiation.

- e.g. UV (185 - 400 nm) / Visible (400 - 800 nm) Spectroscopy, IR Spectroscopy (0.76 - 15 μm)

Principle
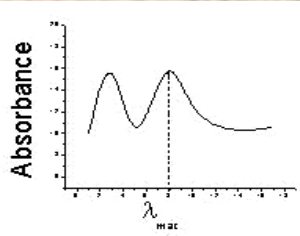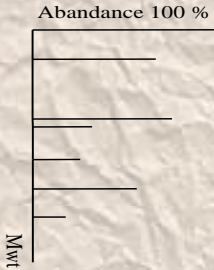
- The UV radiation region extends from 10 nm to 400 nm and the visible radiation region extends from 400 nm to 800 nm.

  Near UV Region: 200 nm to 400 nm

  Far UV Region: below 200 nm

- Far UV spectroscopy is studied under vacuum condition.

- The common solvent used for preparing sample to be analyzed is either ethyl alcohol or hexane.

Spectroscopic Techniques:

Type of technique	Effect of this "E" on the molecule	Shape of chart	Uses of this technique
U.V.	Cause changes in the electronic energy levels within a molecule Excitation of elec. from lower level to higher level		Identify for conjugation (= - =)
I.R	Vibration for bond between two atoms		Identify for the function J/gps in the molecule
M.S	Fragmentation of the molecule to small parts	Abandance 100 % Mwt	Identify through wt. and M.wt. of some fragment to identify the structure
N.M.R	Microwave cause resonance of nucleus of atom under effect of strong magnet	δ 12 0	Identification for the types of "H" in the compound and the structure

Chromophores is the atoms or groups responsible to absorption
N, S, Osuch as;
C=O, C=C, C-C, C=N, C=s

The possible electronic transitions can graphically shown as:
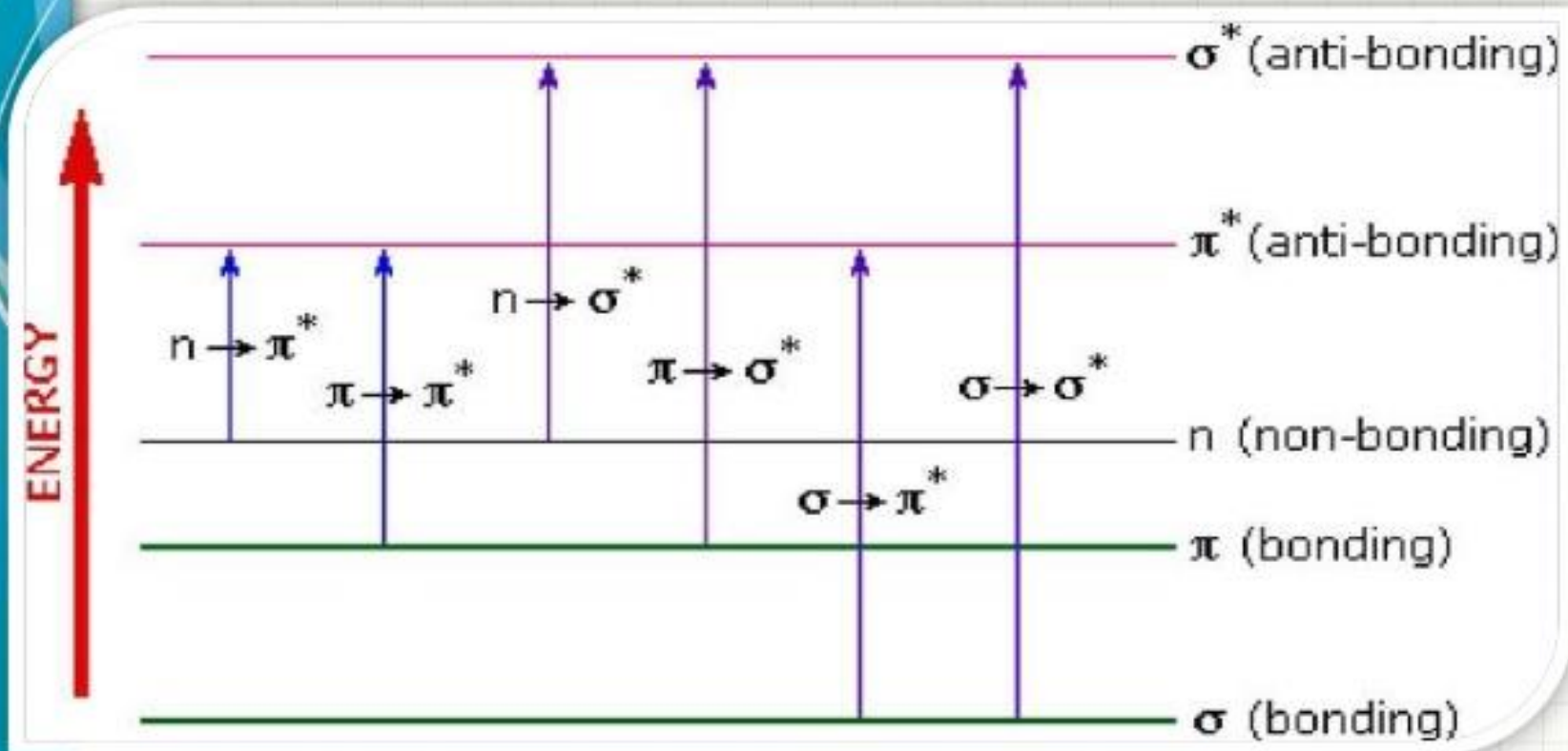
The possible electronic transitions are

1. $\sigma \rightarrow \sigma^*$ transition
2. $\pi \rightarrow \pi^*$ transition
3. $n \rightarrow \sigma^*$ transition
4. $n \rightarrow \pi^*$ transition
5. $\sigma \rightarrow \pi^*$ transition
6. $\pi \rightarrow \sigma^*$ transition

• σ → σ* transition

- σ electron from orbital is excited to corresponding anti-bonding orbital σ*.

- The energy required is large for this transition.

- e.g. Methane (CH_4) has C-H bond only and can undergo σ → σ* transition and shows absorbance maxima at 125 nm.

Atomic orbitals

Combine atomic orbitals

Molecular orbitals

E

s s

Subtract

Add

Antibonding orbital, σ_s^*

Bonding orbital, σ_s

out of phase combination = σ^* MO

in-phase combination = σ MO
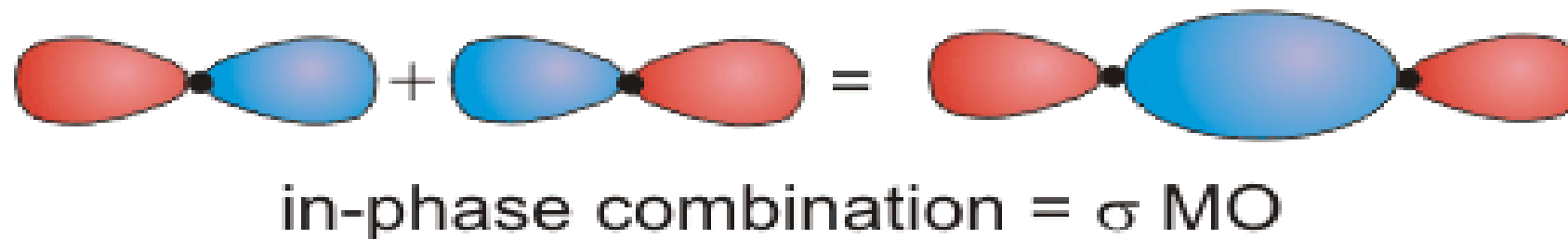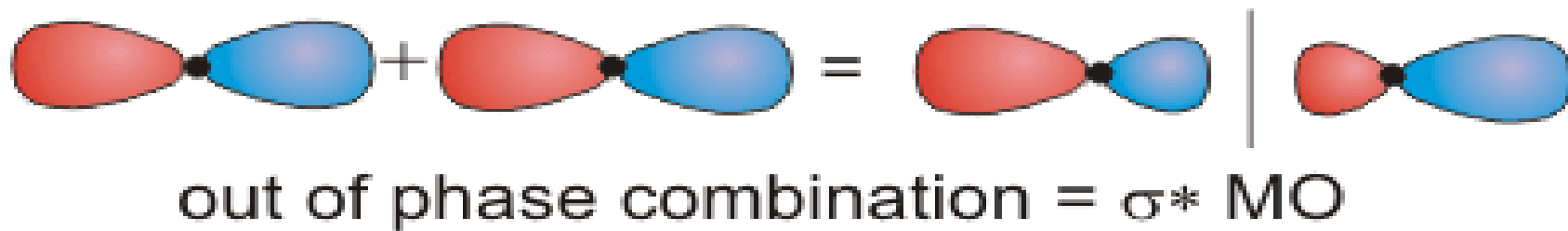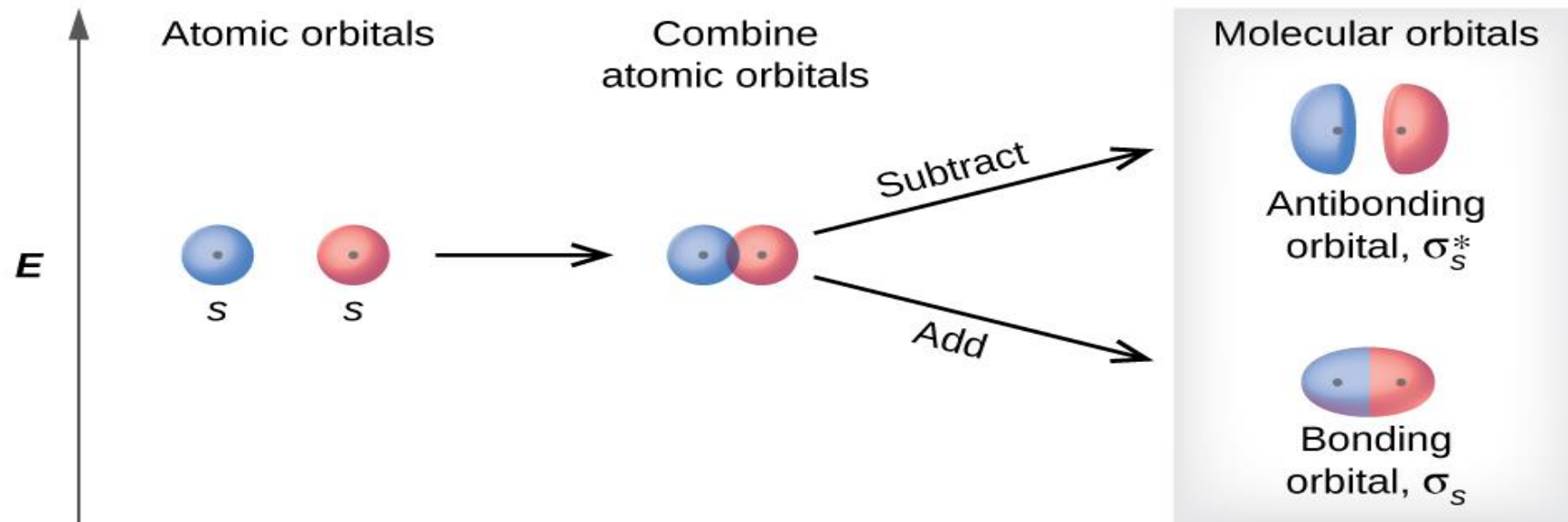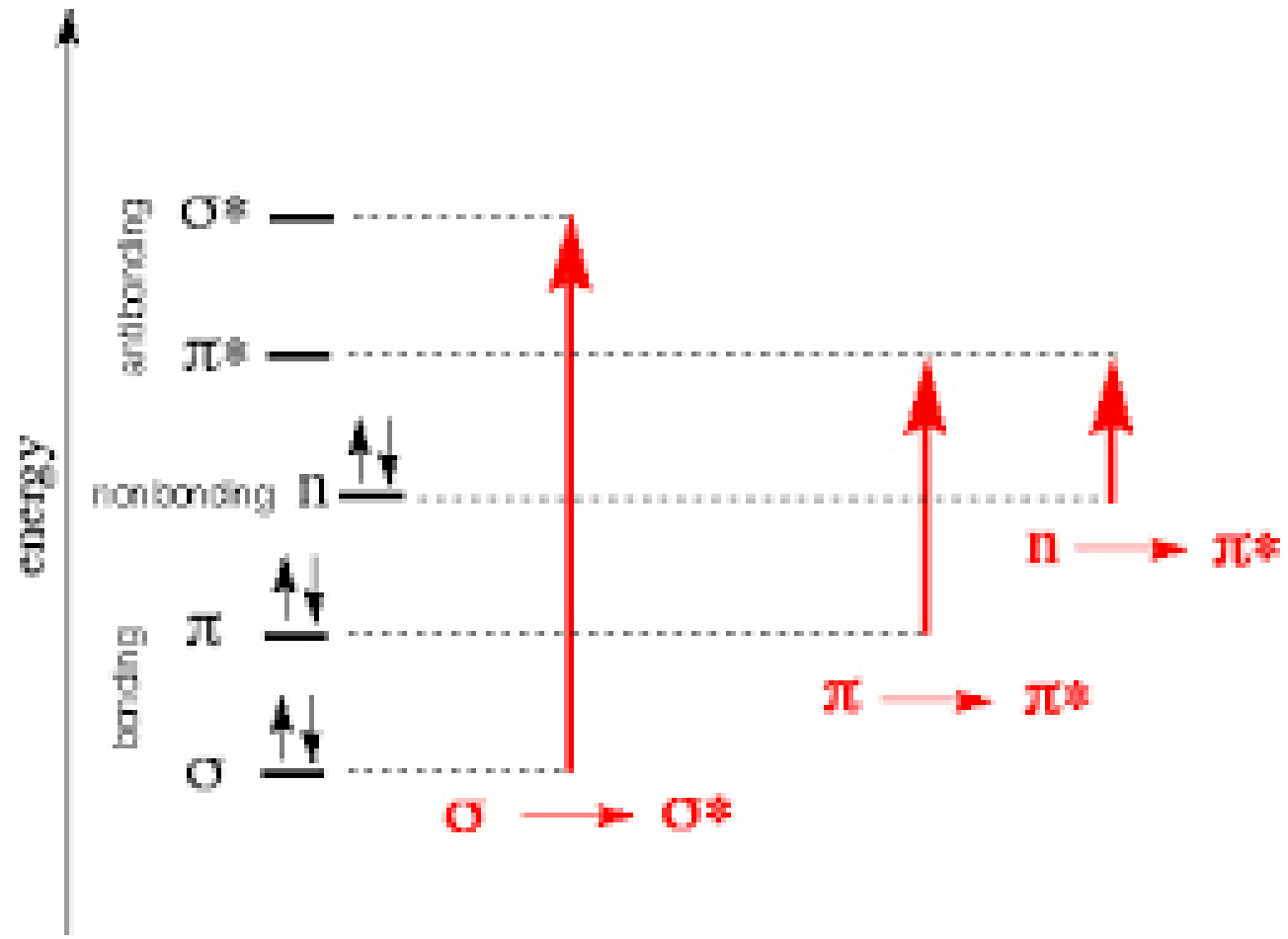
2 — $\pi \rightarrow \pi^*$ transition

- π electron in a bonding orbital is excited to corresponding anti-bonding orbital π^*.

- Compounds containing multiple bonds like alkenes, alkynes, carbonyl, nitriles, aromatic compounds, etc undergo $\pi \rightarrow \pi^*$ transitions.

- e.g. Alkenes generally absorb in the region 170 to 205 nm.

increasing energy of orbitals

combine out-of-phase

combine in-phase

$2\times$

out-of-phase combination of p orbitals gives a π^* orbital

π^* orbital *higher* in energy than carbon p orbital

nodal plane between the two atoms

in-phase combination of p orbitals gives a π orbital

π orbital *lower* in energy than carbon p orbital
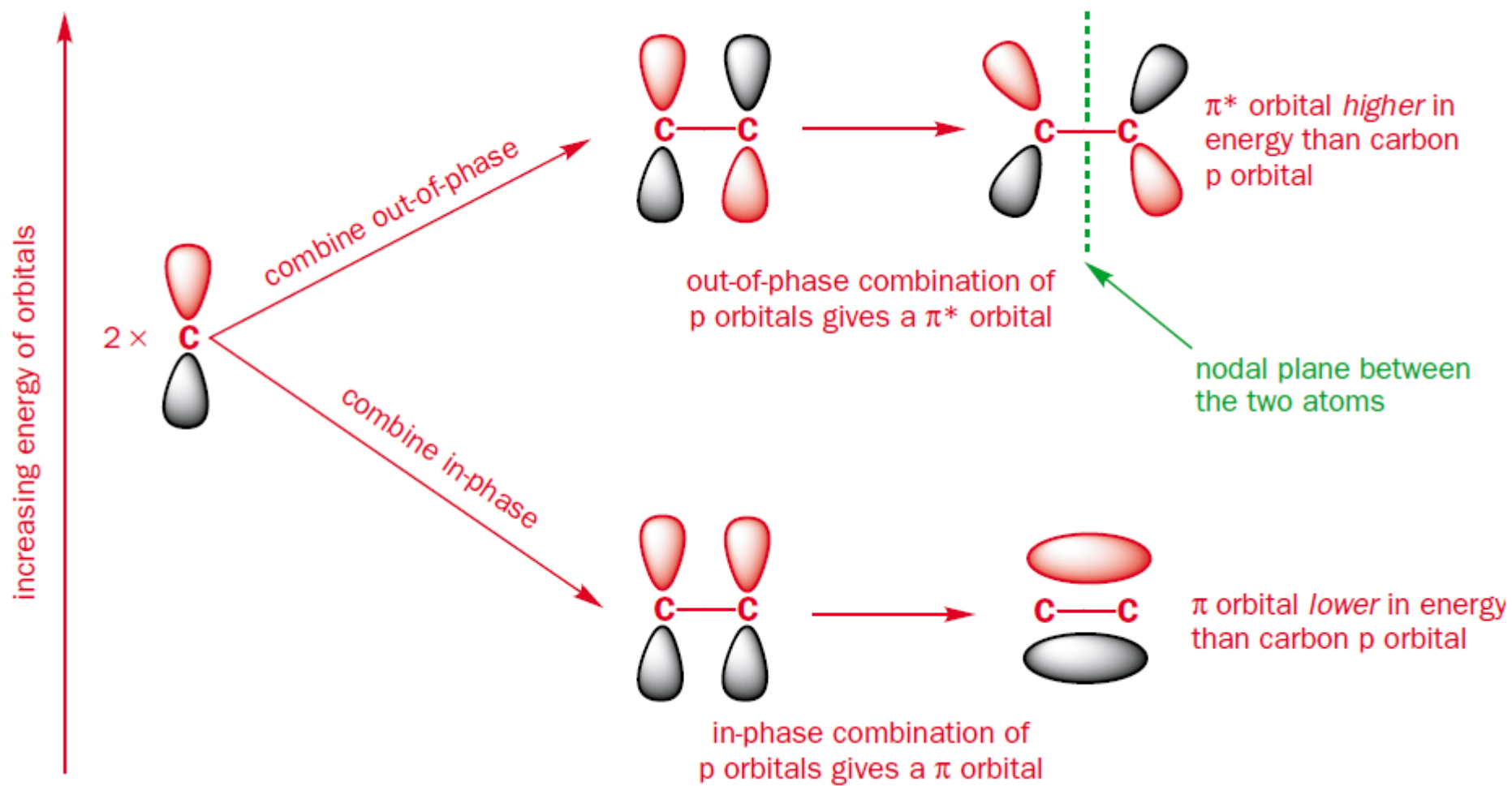
• n → π* transition

- An electron from non-bonding orbital is promoted to anti-bonding π* orbital.

- Compounds containing double bond involving hetero atoms (C=O, C≡N, N=O) undergo such transitions.

- n → π* transitions require minimum energy and show absorption at longer wavelength around 300 nm.

Chromophore

The part of a molecule responsible for imparting color, are called as chromospheres.

OR

The functional groups containing multiple bonds capable of absorbing radiations above 200 nm due to n → π* & π → π* transitions.

e.g. NO_2, N=O, C=O, C=N, C≡N, C=C, C=S, etc

Chromophore

To interpretate UV – visible spectrum following points should be noted:

1. Non-conjugated alkenes show an intense absorption below 200 nm & are therefore inaccessible to UV spectrophotometer.

2. Non-conjugated carbonyl group compound give a weak absorption band in the 200 - 300 nm region.

Chromophore

e.g. Acetone which has $\lambda_{max} = 279$ nm

and that cyclohexane has $\lambda_{max} = 291$ nm.

When double bonds are conjugated in a compound λ_{max} is shifted to longer wavelength.

e.g. 1,5 - hexadiene has $\lambda_{max} = 178$ nm

2,4 - hexadiene has $\lambda_{max} = 227$ nm

Chromophore

3. Conjugation of C=C and carbonyl group shifts the λ_{max} of both groups to longer wavelength.

e.g. Ethylene has λ_{max} = 171 nm

    Acetone has λ_{max} = 279 nm

$H_2C = CH_2$

$$\underset{H_3C}{}\overset{\overset{\displaystyle O}{\|}}{\underset{}{C}}\underset{CH_3}{}$$

    Crotonaldehyde has λ_{max} = 290 nm

$$H_2C = \underset{}{}\overset{\overset{\displaystyle O}{\|}}{C}\underset{CH_3}{}$$

Auxochrome

The functional groups attached to a chromophore which modifies the ability of the chromophore to absorb light , altering the wavelength or intensity of absorption.

OR

The functional group with non-bonding electrons that does not absorb radiation in near UV region but when attached to a chromophore alters the wavelength & intensity of absorption.

Auxochrome

e.g. Benzene λ_{max} = 255 nm

Phenol λ_{max} = 270 nm

Aniline λ_{max} = 280 nm

The π- π^* transitions in π-molecular orbitals of 1,3-butadiene.

π – Molecular orbitals of 1,3-butadiene

Chromophore

3. Conjugation of C=C and carbonyl group shifts the λ_{max} of both groups to longer wavelength.

e.g. Ethylene has λ_{max} = 171 nm

Acetone has λ_{max} = 279 nm

$H_2C=CH_2$

$$H_3C-\underset{\overset{\|}{O}}{C}-CH_3$$

Crotonaldehyde has λ_{max} = 290 nm

$$H_2C=\underset{\overset{\|}{O}}{C}-CH_3$$
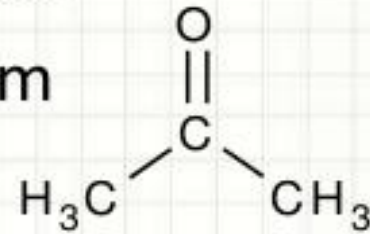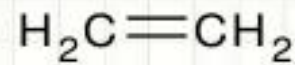
Chromophore
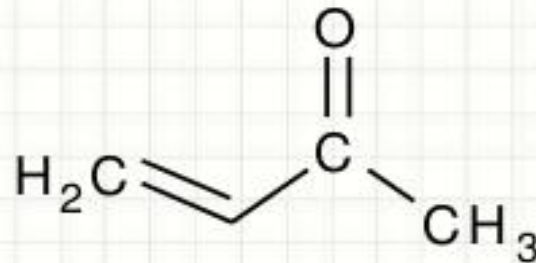
e.g. Acetone which has λ_{max} = 279 nm
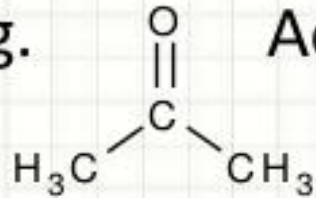
and that cyclohexane has λ_{max} = 291 nm.
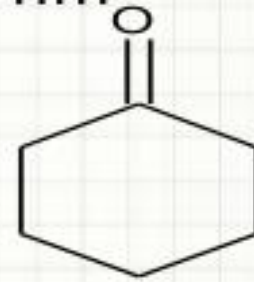
When double bonds are conjugated in a compound λ_{max} is shifted to longer wavelength.

e.g. 1,5 - hexadiene has λ_{max} = 178 nm

2,4 - hexadiene has λ_{max} = 227 nm
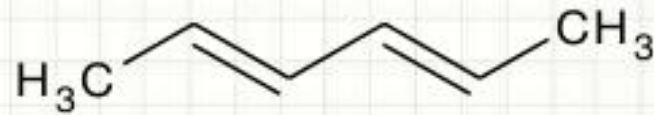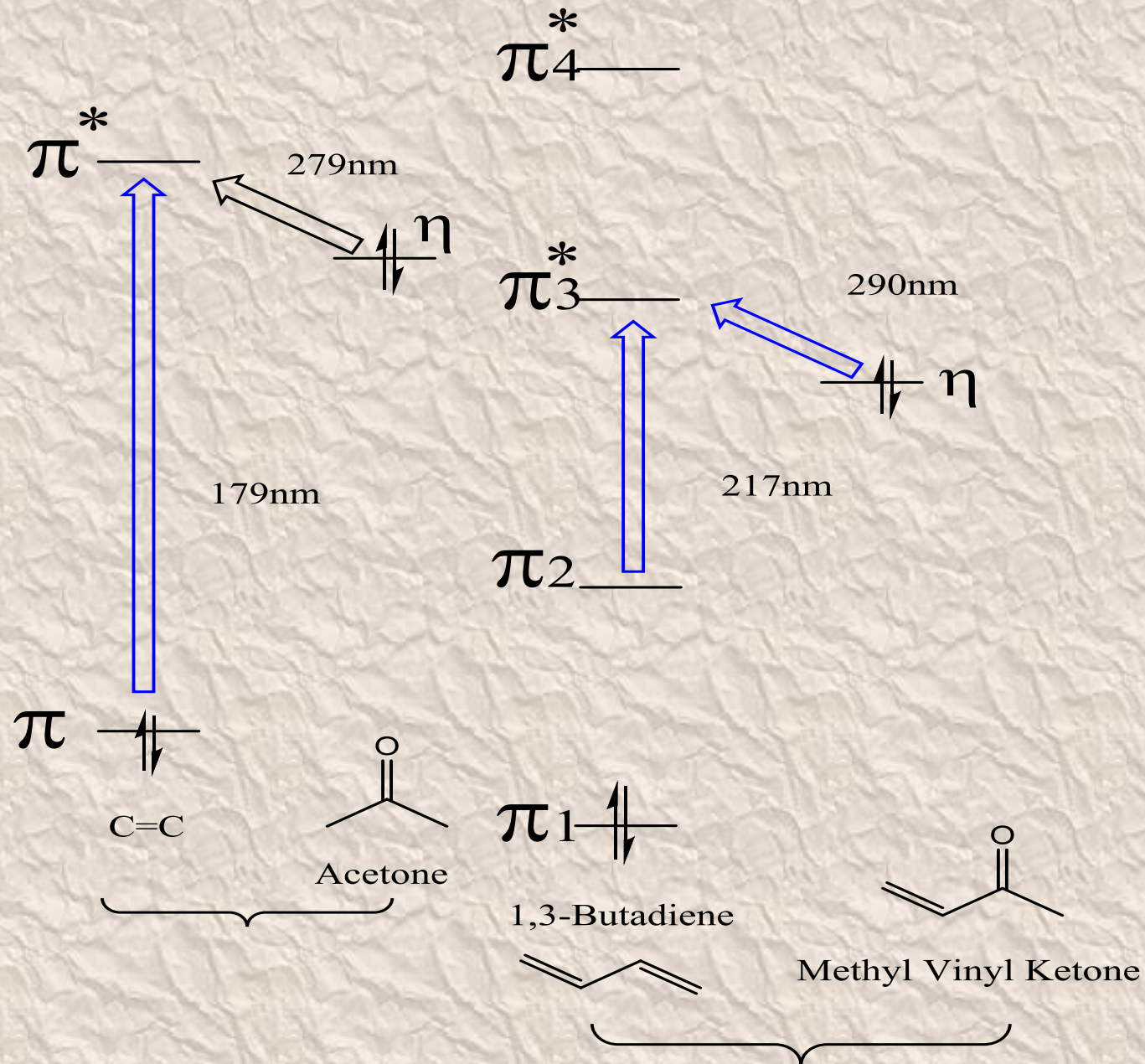
The Electronic Transitions of C=C, Acetone, 1,3-butadiene and Methyl vinyl ketone

Auxochrome

The functional groups attached to a chromophore which modifies the ability of the chromophore to absorb light , altering the wavelength or intensity of absorption.

OR

The functional group with non-bonding electrons that does not absorb radiation in near UV region but when attached to a chromophore alters the wavelength & intensity of absorption.

Auxochrome

e.g.   Benzene λ_{max} = 255 nm

Phenol λ_{max} = 270 nm
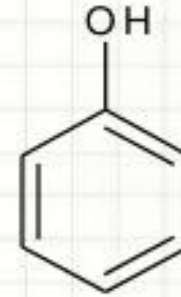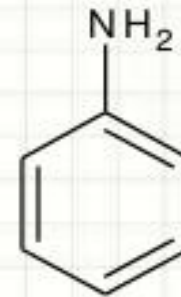
Aniline λ_{max} = 280 nm

Follow the Ultra-Violet Spectroscopy

Woodward-Fieser rules

- In this lesson we discuss a few examples of how we can utilize the **Woodward-Fieser** rules to determine the wavelength of maximum absorption for some molecules. **You have to** read up the first two sections on the **Woodward rules to calculate the λmax for conjugated dienes** and **the Woodward rules to calculate the λmax for α,β-unsaturated carbonyl compounds**.

The Numerical values for Woodward-Fieser rules are in the following tables:

S	Conjugated polyenes	Base absorption (nm)
1	Homoannular diene	253
2	Heteroannular diene	214
	Function	
3	Alkyl	5
4	-OCOR	0
5	-OR	6
6	-SR	30
7	-Cl, -Br	5
8	$-NR_2$	60
9	Extended conjugation	30
10	**Exocyclic double bond**	5

It is recommended that you learn on how to apply these values on the structures and then you have to calculate the λmax value.

In these sample problems you will be shown the structure, then the structure is highlighted to show you key features which would affect the λmax of the molecule. Then the table will show you the solutions on how to solve to get the wavelength of maximum absorption, with a final calculated λmax using the Woodward-Fieser rules. In some cases if we have an observed λmax for comparison, it may be given as well.

Example 1
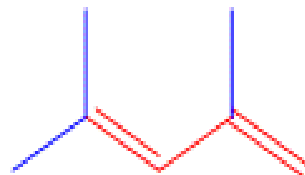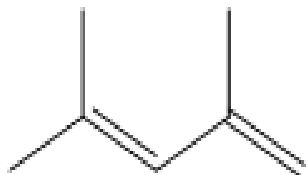
2,4-dimethylpenta-1,3-diene

Woodward Component	Contribution
Parent base- Heteroannular Diene	+ 214 nm
Substituents- 3 alkyl groups	3 x 5 = 15 nm
Calculated λmax	**229 nm**
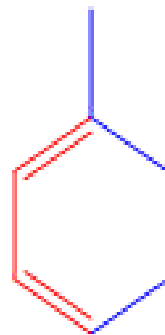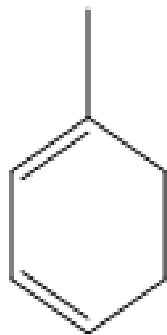
Example 2

Name of Compound	1-methylcyclohexa-1,3-diene
Woodward Component	**Contribution**
Parent base- Homoannular Diene	+ 253 nm
Substituents- 3 alkyl groups	3 x 5 = + 15 nm
Calculated λmax	**268 nm**

Example 3
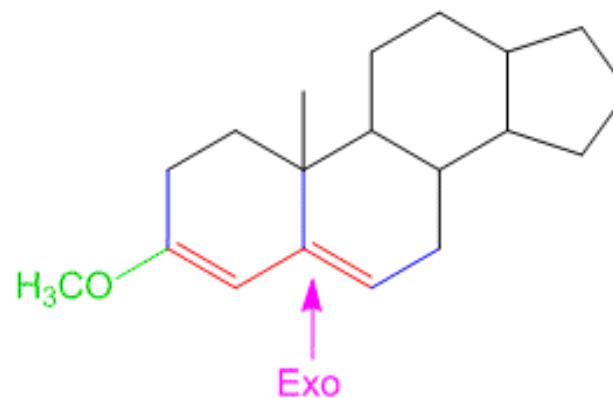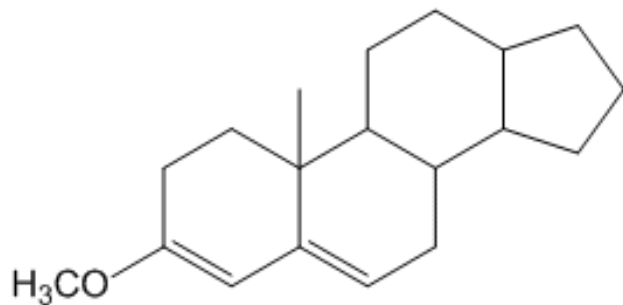
	3-methoxy-10-methyl-2,7,8,9,10,11,12,13,14,15,16,17-dodecahydro-1H-cyclopenta[a]phenanthrene
Name of Compound	
Woodward Component	**Contribution**
Parent base- Heteroannular Diene	214 nm
Substituents- 3 alkyl groups	3 x 5 = 15 nm
1 alkoxy group	
Exocyclic Double Bond	+ 6 nm + 5 nm
Calculated λmax	**240 nm**

Example 4

Name of Compound	10,13-dimethyl-2,3,9,10,11,12,13,15,16,17-decahydro-1H-cyclopenta[a]phenanthrene
Woodward Component	**Contribution**
Parent base- Heteroannular	+ 214 nm
Substituents- 5 alkyl groups 1 Double bond extending conjugation	5 x 5 = + 25 nm + 30 nm
3 Exocyclic Double Bond	+ 15 nm
Calculated λmax	**284 nm**
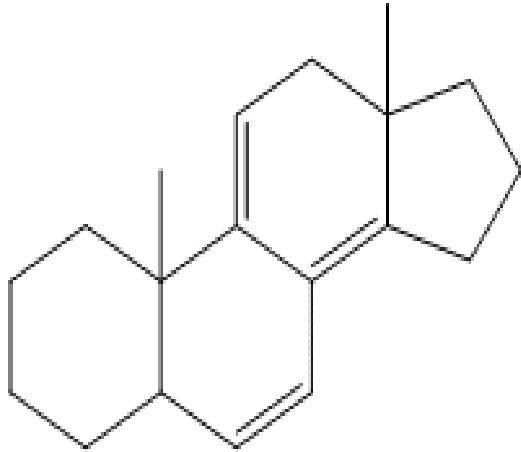
Example 5

Note- In this example the molecule **contains both, a homoannular diene system and a heteroannular diene** system. In such a molecule the core chromophore is considered to be the homoannular system and accordingly the calculations are performed.

Homoannular system

Component	Contribution
Parent base- Homoannular	+ 253 nm
Substituents– 5 alkyl substituents Double bond extending conjugation	5 x 5 = + 25 nm + 30 nm
3 Exocyclic double bonds	3 x 5 = + 15 nm
Calculated λ_{max}	**323 nm**

Parent base- α,β-unsaturated carbonyl compound cyclohexenone	+ 214 nm
Substituents: 5 alkyl group	+ 25 nm
Cl	5
OH	+ 6 nm
Other Effects: 2 Double bonds extending conjugation	+ 60 nm
3 Exocyclic double bond	+ 15 nm
Calculated λ_{max}	325 nm

Cl

COOH

OH
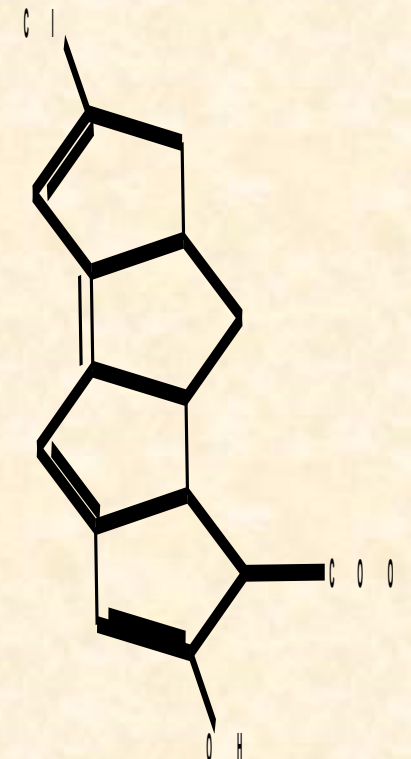
Calculation of the λmax of α,β-unsaturated carbonyl compounds

In this lesson we discuss a few examples of how we can utilize the **Woodward-Fieser** rules to determine the wavelength of maximum absorption for some molecules. **The Woodward rules to calculate the λmax for α,β-unsaturated carbonyl compounds**.

The Numerical values for Woodward-Fieser rules are in the following tables:

S	α , β- Unsaturated parent	Base absorption (nm)
1	Acyclic or six membered or higher ring ketones	215
2	Five-membered ring ketone	205
3	Aldehydes	210
4	Carboxylic acids and esters	195
5	Extended conjugation	30
6	Homodienic component	39
7	Exocyclic double bond	5

S	Substituent	α	β	γ or higher
1	Alkyl (R-)	10	12	18
2	Hydroxyl (-OH)	35	30	50
3	Alkoxyl (RO-)	35	30	17
4	Acetoxyl (CH_3COO-)	6	6	6
5	Dialkylamino (-NR_2	-	95	-
6	Chloro (Cl-)	15	12	-
7	Bromo (Br-)	25	30	-
8	Alkylthio (RS-)	-	85	-

It is recommended that you learn on how to apply these values on the structures and then you have to calculate the λmax value.

In these sample problems you will be shown the structure, then the structure is highlighted to show you key features which would affect the λmax of the molecule. Then the table will show you the solutions on how to solve to get the wavelength of maximum absorption of α,β-unsaturated carbonyl compounds, with a final calculated λmax using the Woodward-Fieser rules. In some cases if we have an observed λmax for comparison, it may be given as well.
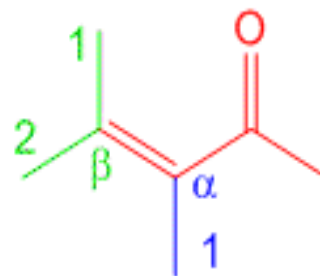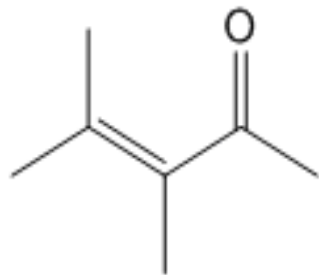
Name of Compound	3,4-dimethylpent-3-en-2-one
Component	**Contribution**
Parent base- α,β-unsaturated carbonyl compound	+ 215 nm
Substituents at α-position- 1 alkyl group	+ 10 nm
Substituents at β-position- 2 alkyl groups	2 x 12 = 24 nm
Calculated λ_{max}	**249 nm**

Example 1
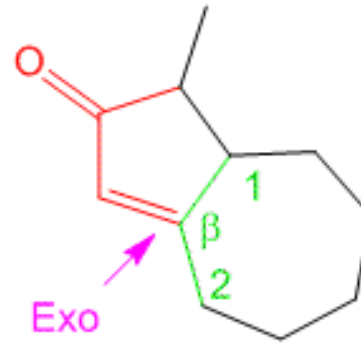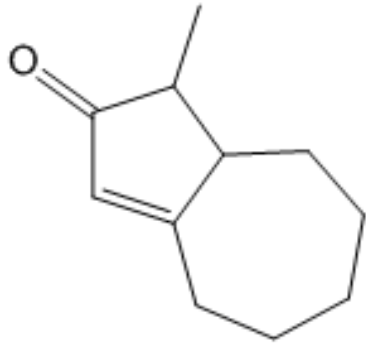
Name of Compound	1-methyl-4,5,6,7,8,8a-hexahydroazulen-2(1H)-one
Component	**Contribution**
Parent base- cyclopentenone	+ 205 nm
Substituents at α-position	0
Substituents at β-position- 2 alkyl groups	2 x 12= + 24 nm
1 Exocyclic Double Bond	+ 5 nm
Calculated λ_{max}	**234 nm**

Example 2
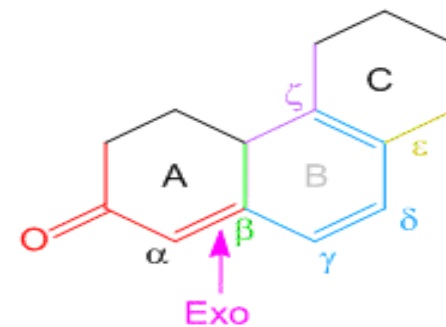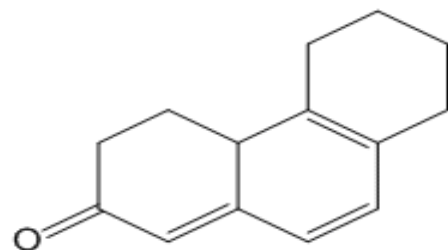
Name of Compound	4,4a,5,6,7,8-hexahydrophenanthren-2(3H)-one
Component	**Contribution**
Parent base- α,β-unsaturated carbonyl compound cyclohexenone	+ 215 nm
Substituents at α-position:	0
Substituents at β-position: 1 alkyl group	+ 12 nm
Substituents at γ-position: 3 alkyl group	3 x 18 = + 54 nm
Other Effects: 2 Double bonds extending conjugation	2 x 30 = + 60 nm
Homoannular Diene system in ring B	+ 35 nm
1 Exocyclic double bond	+ 5 nm
Calculated λ_{max}	**381 nm**

Parent base- α,β-unsaturated carbonyl compound cyclohexenone	**+ 195 nm**
Substituents at α-position:	+ 10nm
Substituents at β-position: 1 alkyl group	+ 12 nm
Substituents at γ-position: 3 alkyl group	3 x 18 = + 54 nm
γ- Cl	0
Other Effects: 2 Double bonds extending conjugation	2 x 30 = + 60 nm
Homoannular Diene system in ring B	+ 35 nm
2 Exocyclic double bond	+ 10nm
Calculated λ_{max}	376 nm
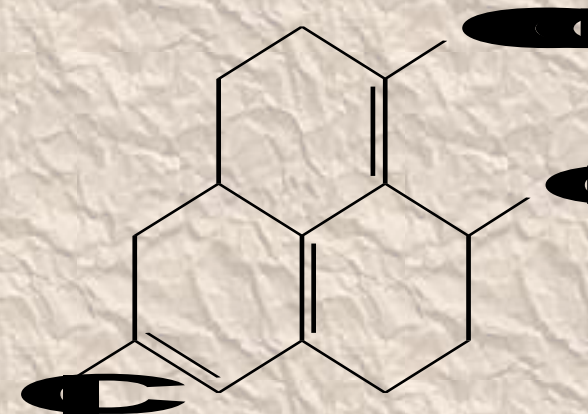
Parent base- α,β-unsaturated carbonyl compound Aldehyde	**+ 210 nm**
Substituents at α-position:	+ 10nm
Substituents at β-position: 1 alkyl group	+ 12 nm
Substituents at γ-position: 4 alkyl group	4 x 18 = + 72 nm
γ- CH3	+18
γ- Cl	0
Other Effects: 2 Double bonds extending conjugation	3 x 30 = + 90 nm
Homoannular Diene system in ring B, D	2 x 39 nm
4 Exocyclic double bond	+ 20nm
Calculated λ_{max}	510 nm
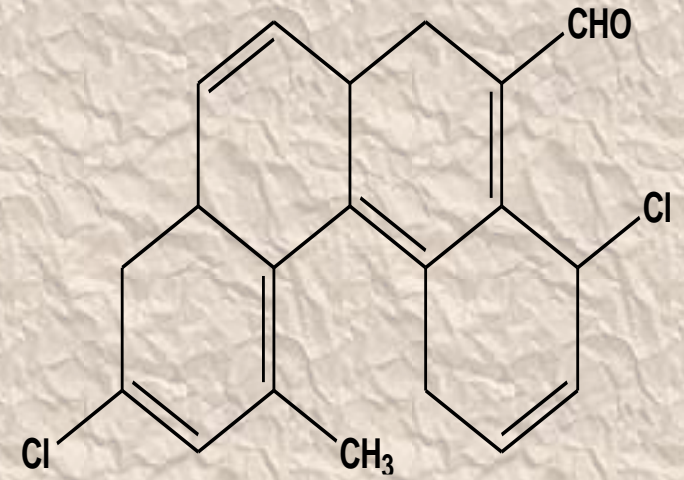
IR

Infrared Spectroscopy

Infrared spectroscopy (IR spectroscopy) is the spectroscopy that deals with the infrared region of the electromagnetic spectrum, that is light with a longer wavelength and lower frequency than visible light. It covers a range of techniques, mostly based on absorption spectroscopy. As with all spectroscopic techniques, it can be used to identify and study chemicals. A common laboratory instrument that uses this technique is a Fourier transform infrared (FTIR) spectrometer. The IR spectroscopy theory utilizes the concept that molecules tend to absorb specific frequencies of light that are characteristic of the corresponding structure of the molecules.

Infrared spectroscopy (IR spectroscopy or vibrational spectroscopy) involves the interaction of infrared radiation with matter. It covers a range of techniques, mostly based on absorption spectroscopy. As with all spectroscopic techniques, it can be used to identify and study chemical substances. Samples may be solid, liquid, or gas. The method or technique of infrared spectroscopy is conducted with an instrument called an infrared spectrometer to produce an infrared spectrum.

Typical units of frequency used in IR spectra are wave numbers, with the symbol cm−1. Units of IR wavelength are commonly given in micrometers (formerly called "microns"), symbol μm, which are related to wave numbers in a reciprocal way. A common laboratory instrument that uses this technique is a Fourier transform infrared (FTIR) spectrometer. Two-dimensional IR is also possible.

The infrared portion of the electromagnetic spectrum is usually divided into three regions; the near- (0.75- 2.5 µm , mid- (2.5- 16 µm) and far- infrared (25- 1000 µm), named for their relation to the visible spectrum. The higher-energy near-IR, approximately 14000–4000 cm−1 (0.7–2.5 µm wavelength) can excite overtone or harmonic molecular vibrations. The mid-infrared, approximately 4000–400 cm−1 (2.5–25 µm) may be used to study the fundamental vibrations and associated rotational-vibrational structure. The far-infrared, approximately 400–10 cm−1 (25–1000 µm), lying adjacent to the microwave region, has low energy and may be used for rotational spectroscopy. The names and classifications of these subregions are conventions, and are only loosely based on the relative molecular or electromagnetic properties.

IR Spectroscopy detects frequencies of infrared light that are absorbed by a molecule. Molecules tend to absorb these specific frequencies of light since they correspond to the frequency of the vibration of bonds in the molecule.

There are two types of vibrational motions:

A)	Stretching deformation: It is a vibrational motion of a bond along the bond axis within a molecule (υ).

B)	Bending deformation: It is a vibrational motion of a bond perpendicular to the bond axis within a molecule (δ).

Normal modes: A molecule can vibrate in many ways, and each way is called a vibrational mode. Linear molecules have $3N - 5$ degrees of vibrational modes whereas nonlinear molecules have $3N - 6$ degrees of vibrational modes (also called vibrational degrees of freedom). As an example H_2O, a non-linear molecule, will have $3 \times 3 - 6 = 3$ degrees of vibrational freedom, or normal modes.

IR Spectroscopy Instrumentation

The instrumentation of infrared spectroscopy is illustrated below. First, a beam of IR light from the source is split into two and passed through the reference ant the sample respectively.
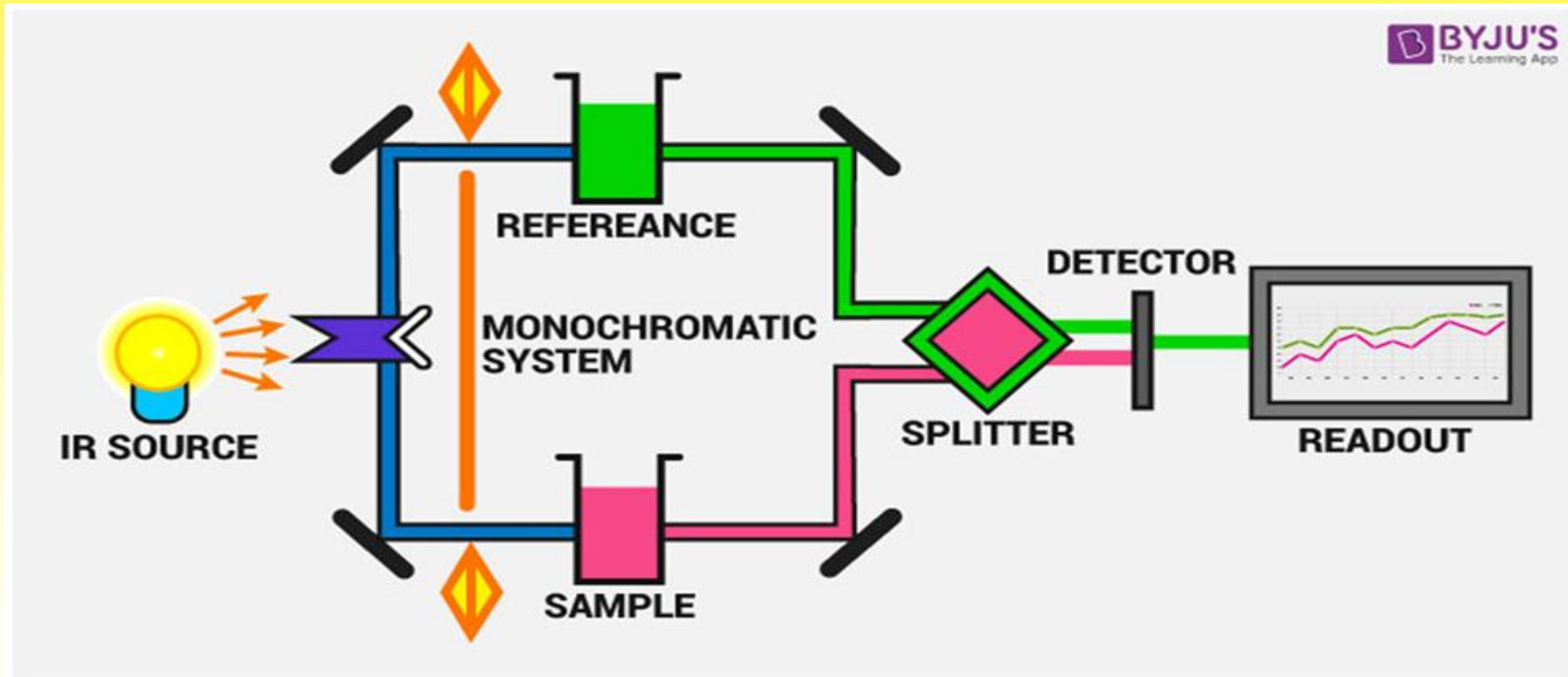
Now, both of these beams are reflected to pass through a splitter and then through a detector. Finally, the required reading is printed out after the processor deciphers the data passed through the detector.

Graph of the IR spectrum
Given below is a sample of typical Infrared Absorption Frequencies.
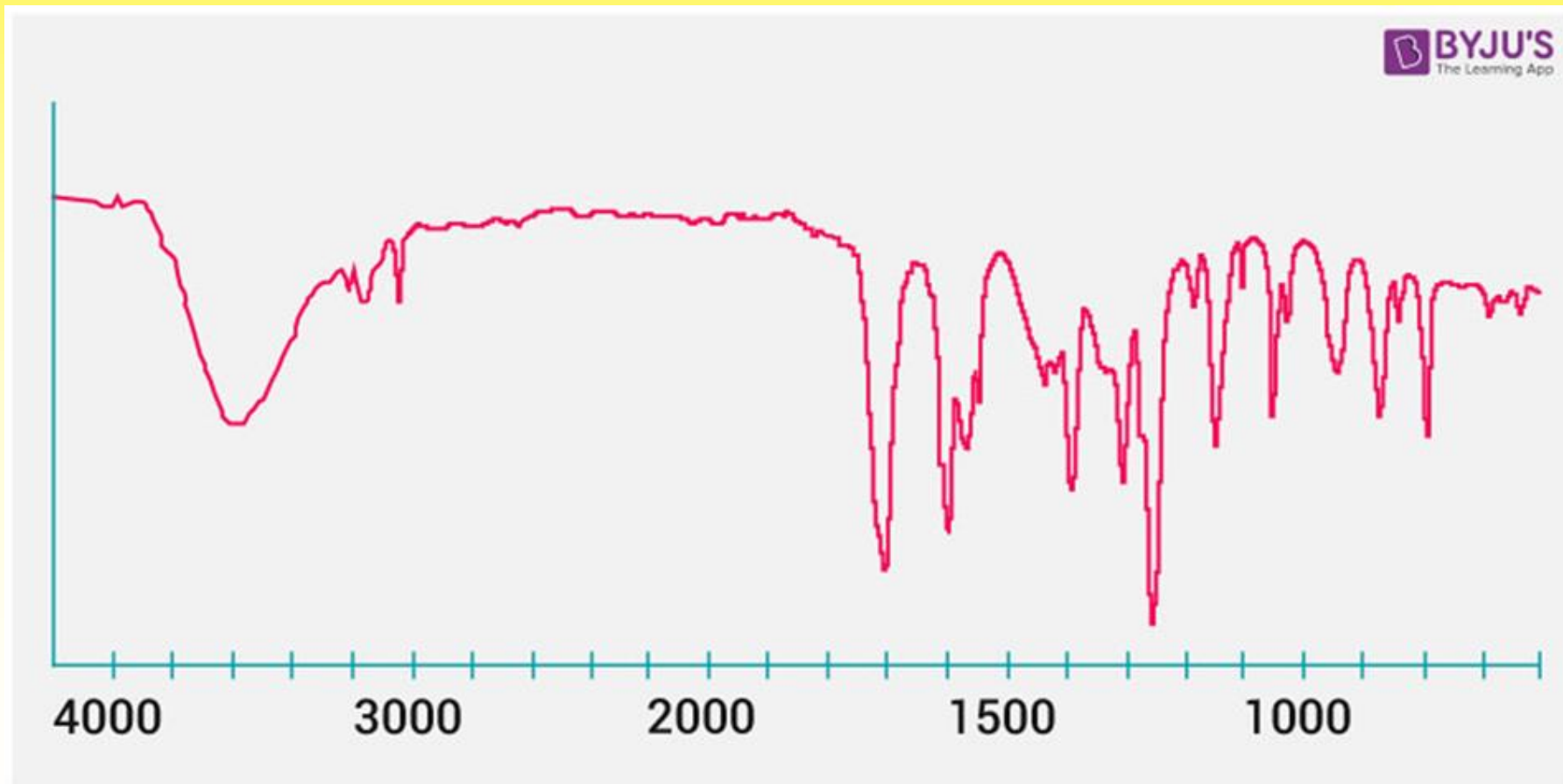
CHARACTERISTIC ABSORPTION BANDS

The IR Spectrum Table is a chart for use during infrared spectroscopy. The table lists IR spectroscopy frequency ranges, appearance of the vibration and absorptions for functional groups.

IR Spectrum Table by Frequency Range

Use the following table when you already know the frequency of your material. Find the frequency range in the first column on the left side of the chart and corresponding values in adjacent columns. (يحفظ الجدول كاملا)

Frequency Range	Absorption (cm^{-1})	Appearance	Group	Compound Class	Comments
4000-3000 cm^{-1}	3650	weak, broad	O-H stretching	alcohol	free
	3350-3310	medium	N-H stretching	secondary amine	
	3500-2500	strong, broad	O-H stretching	carboxylic acid	usually centered on 3000 cm^{-1}
	3610	weak, broad	O-H stretching	phenol	intramolecular bonded
	3400, 3350	strong, broad	NH2 stretching	Amino group	
cm^{-1}	2980, 2890	strong, sharp	C-H stretching	C-H (CH$_3$, CH$_2$, CH) aliphatic	
	3030	medium	C-H stretching	C-H aromatic	
	2700	medium	C-H stretching	O=C-H aldehyde	doublet
	2600-2550	weak	S-H stretching	thiol	
	2349	strong	O=C=O stretching	carbon dioxide	
	2275-2250	strong, broad	N=C=O stretching	isocyanate	

2220	weak	C≡N stretching	nitrile	
2260-2190	weak	C≡C stretching	alkyne	disubstituted
2175-2140	strong	S-C≡N stretching	thiocyanate	
2160-2120	strong	N=N=N stretching	N3 azide	
2150		C=C=O stretching	ketene	
2145-2120	strong	N=C=N stretching	carbodiimide	
2140-1990	strong	N=C=S stretching	isothiocyanate	
2000-1900	medium	C=C=C stretching	allene	
2000		C=C=N stretching	ketenimine	
2000-1650	weak	C-H bending	C-H aromatic compound	overtone

1820, 1760	strong	C=O stretching	anhydride	
1815-1785	strong	C=O stretching	O=C-X acid halide	
1760	strong	C=O stretching	carboxylic acid	monomer
1735	strong	C=O stretching	esters	6-membered lactone
1750	strong	C=O stretching	δ-lactone	γ: 1770
1745	strong	C=O stretching	cyclopentanone	
1720	strong	C=O stretching	aldehyde	
1725	strong	C=O stretching	aliphatic ketone	or cyclohexanone or cyclopentenone
1690	strong	C=O stretching	$CONH_2$ primary amide	
1620	medium	C=N stretching	imine / oxime	
1640	strong	C=O stretching	secondary amide	

1630	strong	C=O stretching	tertiary amide	
1650	strong	C=O stretching	δ-lactam	
1678-1668	weak	C=C stretching	alkene	disubstituted (trans)
1662-1626	medium	C=C stretching	alkene	disubstituted (cis)
1650-1600	medium	C=C stretching	C=C-C=C conjugated alkene	
1620-1610	strong	C=C stretching	C=C-C=O α,β-unsaturated ketone	
1550-1500	strong	N-O stretching	NO_2 nitro group	
1415-1380	strong	S=O stretching	SO_4 sulfate	
1200-1185				

1410-1380	strong	S=O stretching	SO$_2$Cl sulfonyl chloride	
1204-1177				
1400-1000	strong	C-F stretching	fluoro compound	
1372-1335	strong	S=O stretching	sulfonate	
1370-1335	strong	S=O stretching	SO$_2$NH$_2$ sulfonamide	
1170-1155				
1350-1342	strong	S=O stretching	SO$_3$H sulfonic acid	anhydrous
1070-1030	strong	S=O stretching	sulfoxide	
690-515	strong	C-Br stretching	halo compound	
600-500	strong	C-I stretching	halo compound	
880	strong	C-H bending	1,2,4-trisubstituted benzene	
860	strong	C-H bending	1,3-disubstituted benzene	
780	strong	C-H bending	1,4-disubstituted or	
780	strong	C-H bending	1,2,3-trisubstituted benzene	
755	strong	C-H bending	1,2-disubstituted benzene	
700	strong	C-H bending	monosubstituted	
			benzene derivative	

Examples

1-hexyne

$HC \equiv C - (CH_2)_3 - CH_3$

2991 C-H stretch

C=O
Stretch
71715

CH₃ — CH₂ — C — CH₃

2-butanone
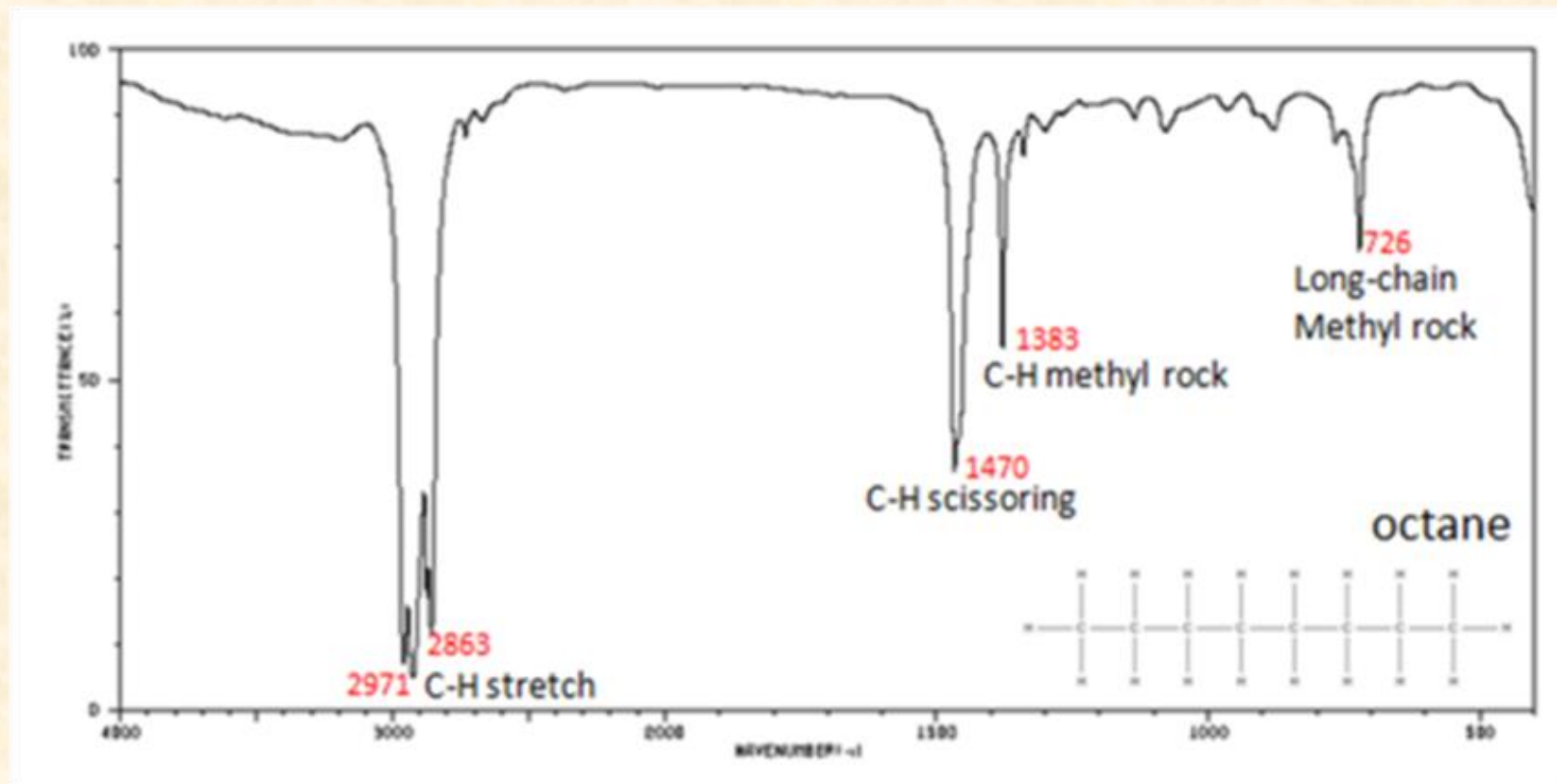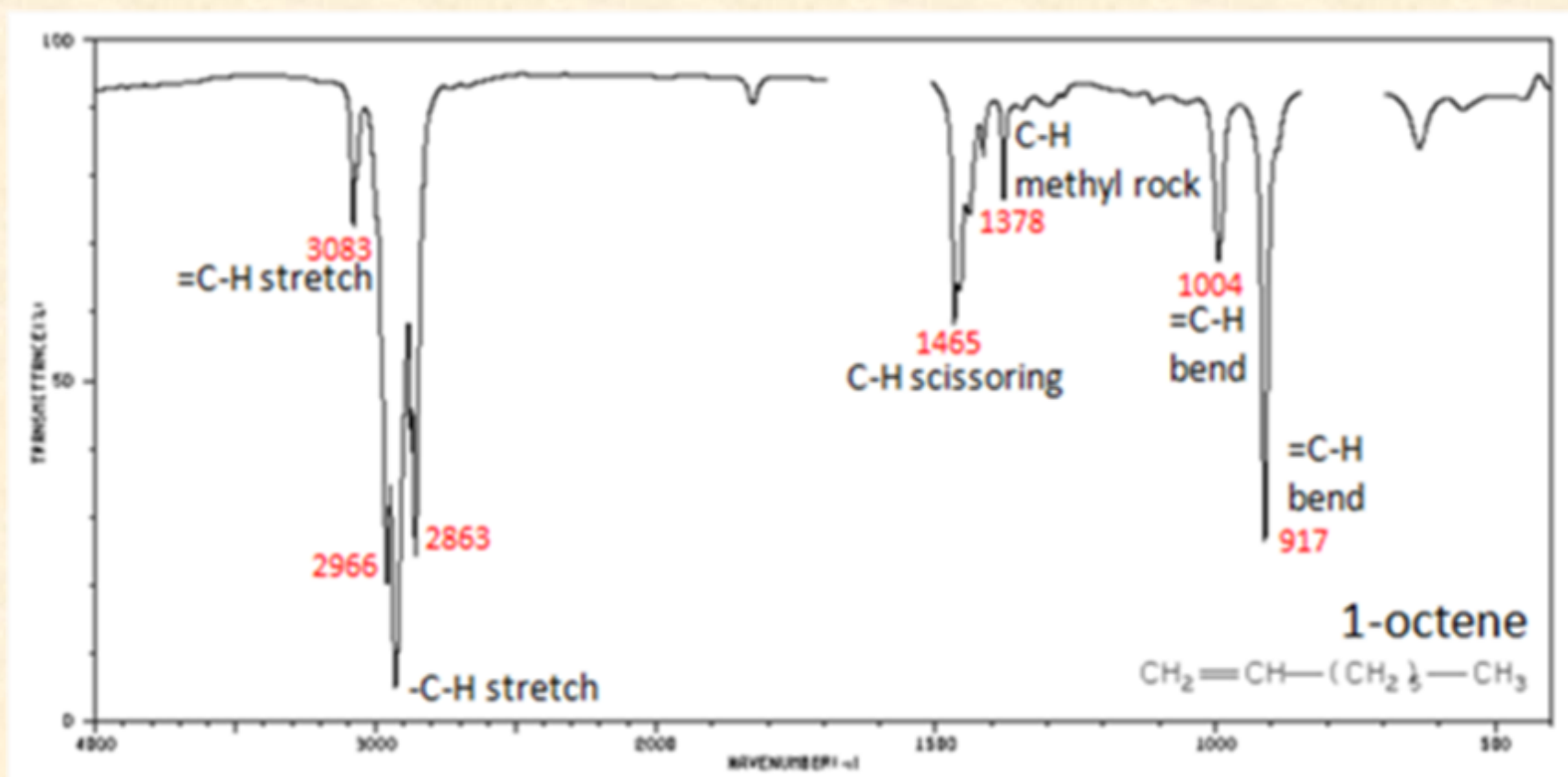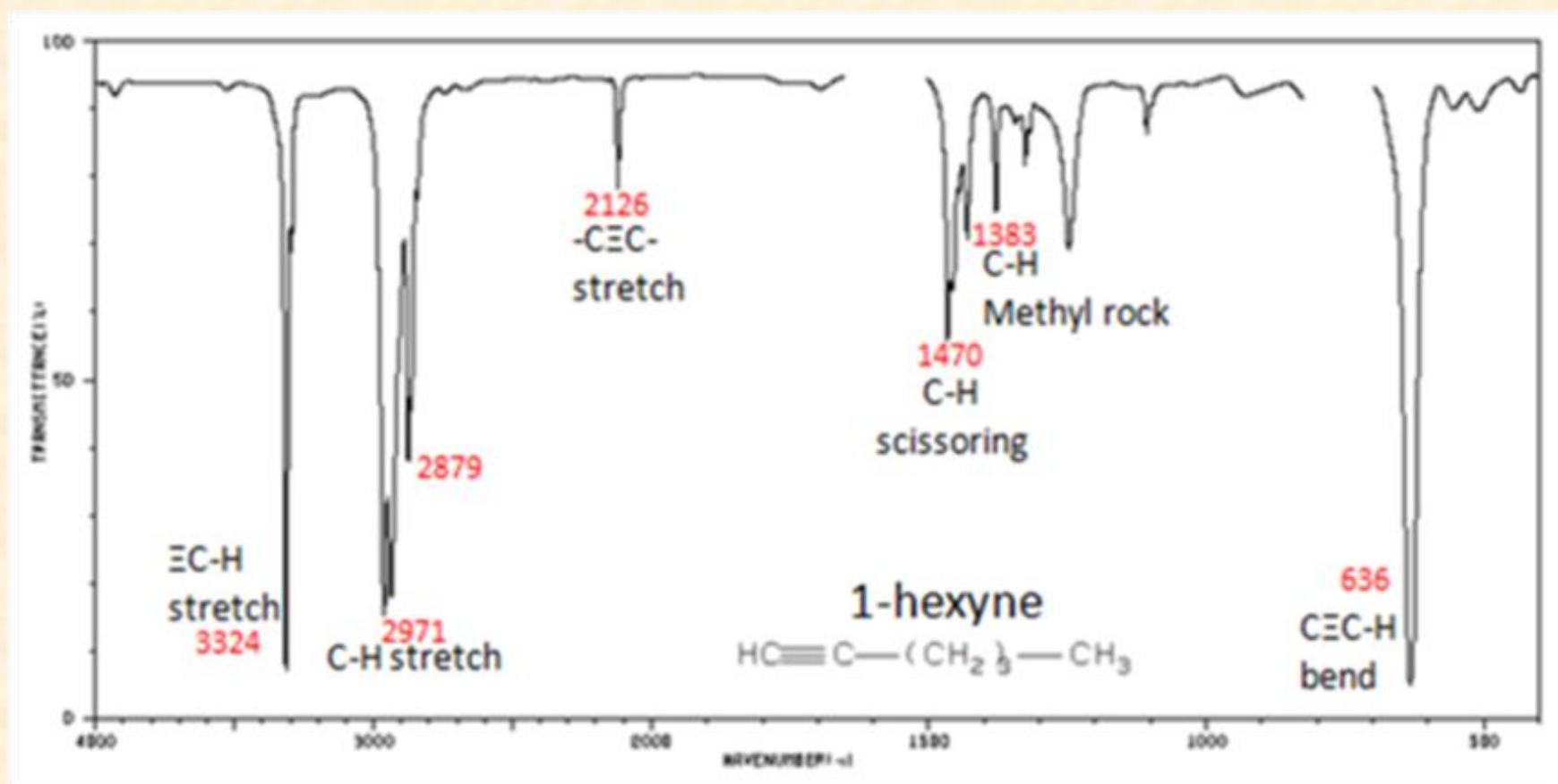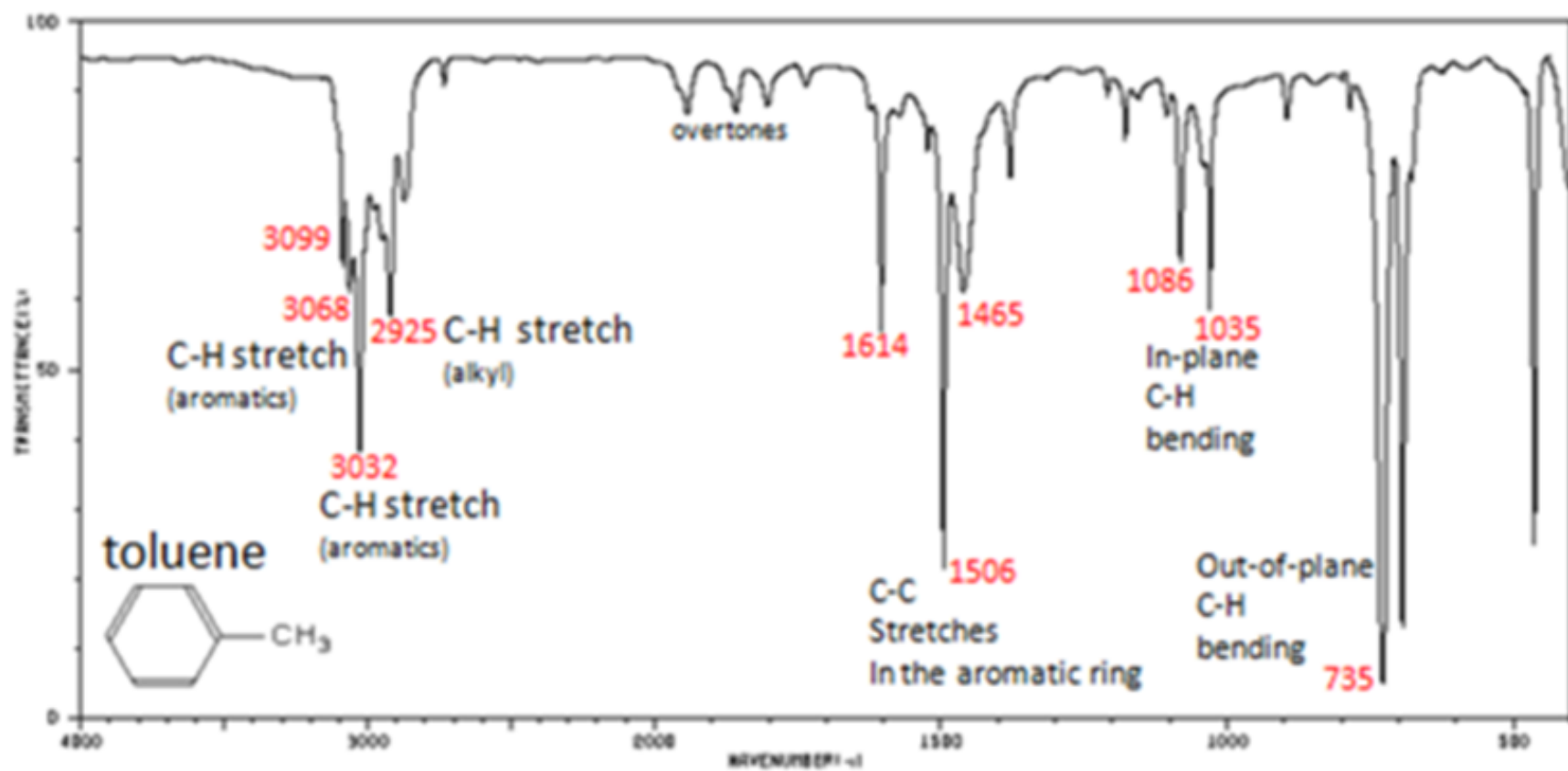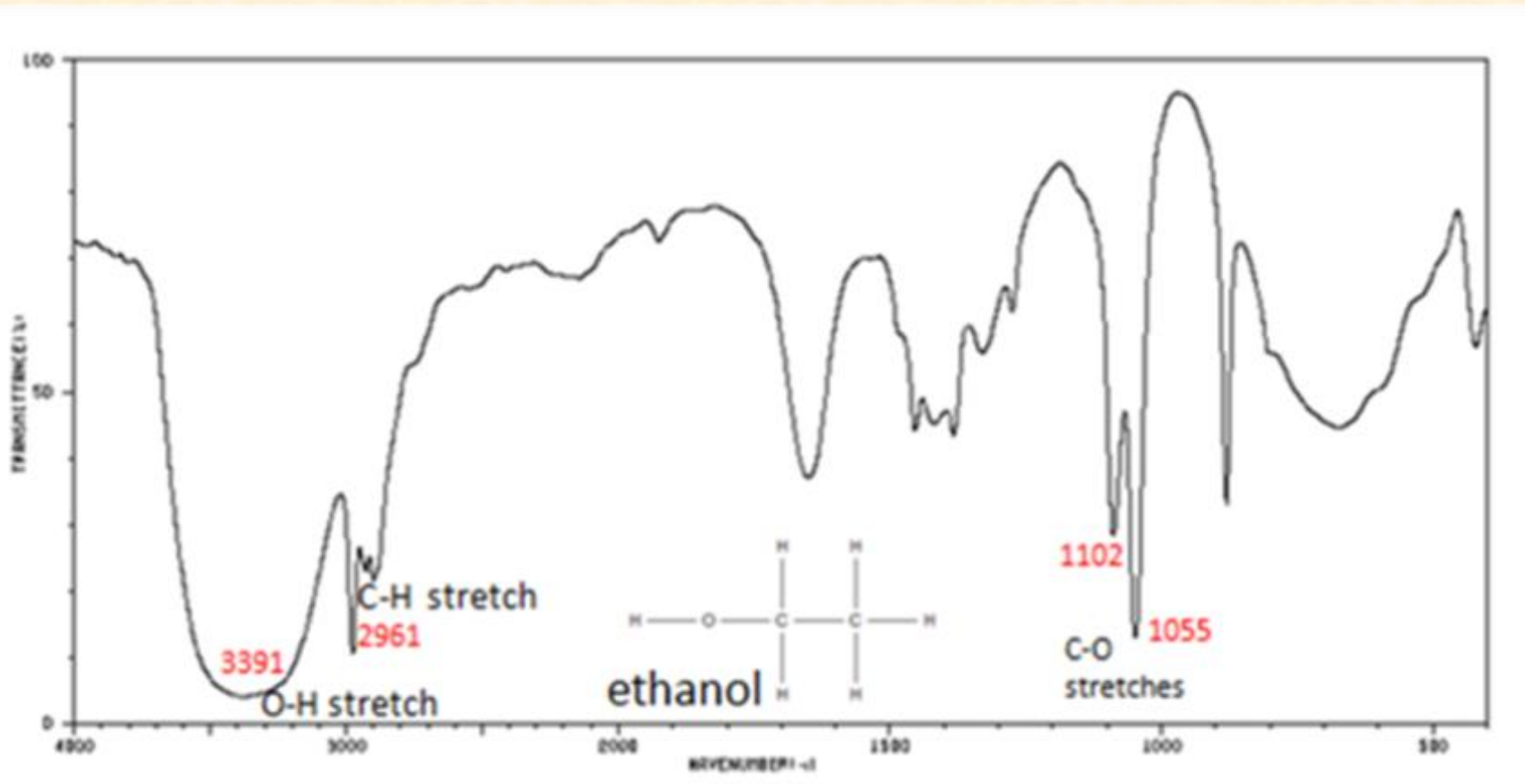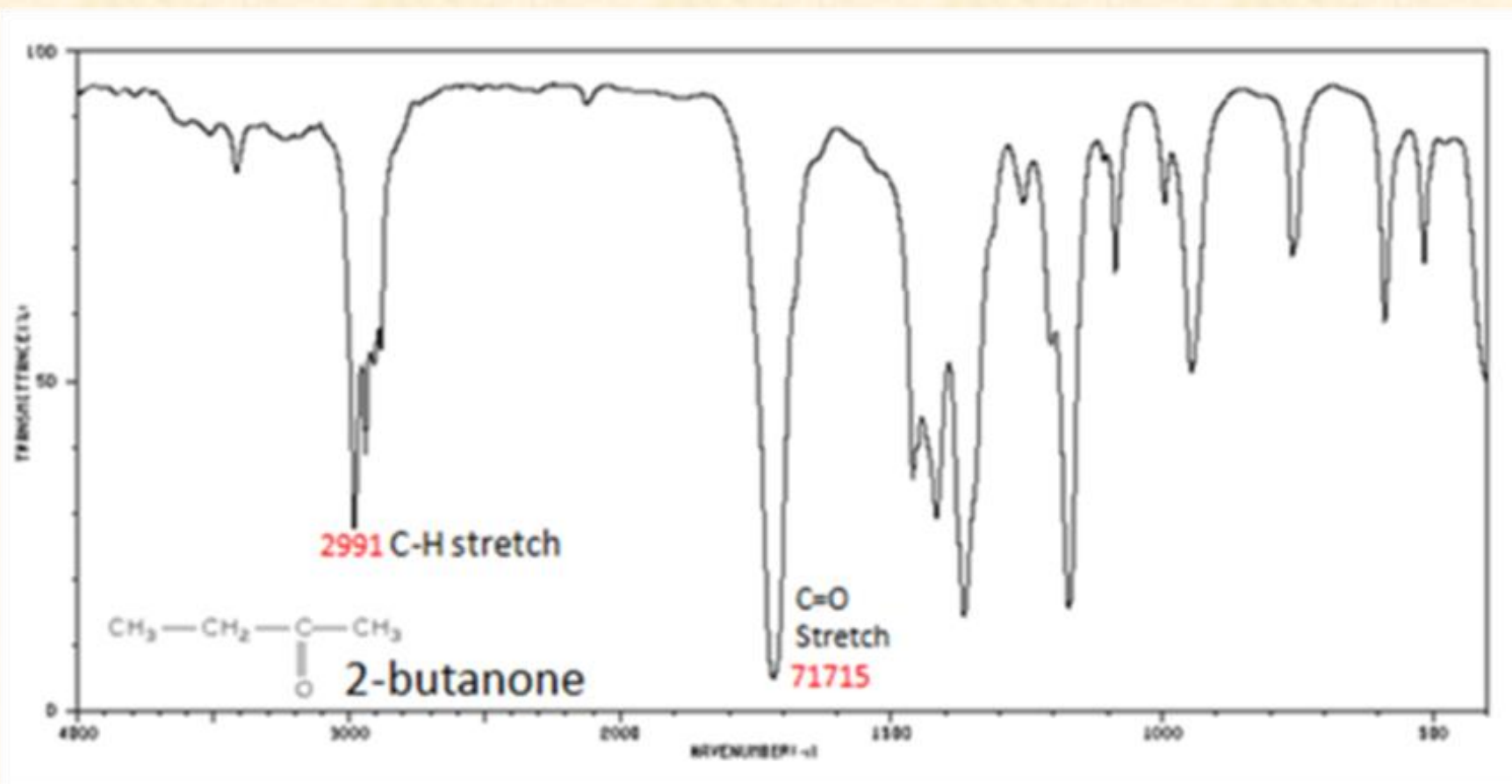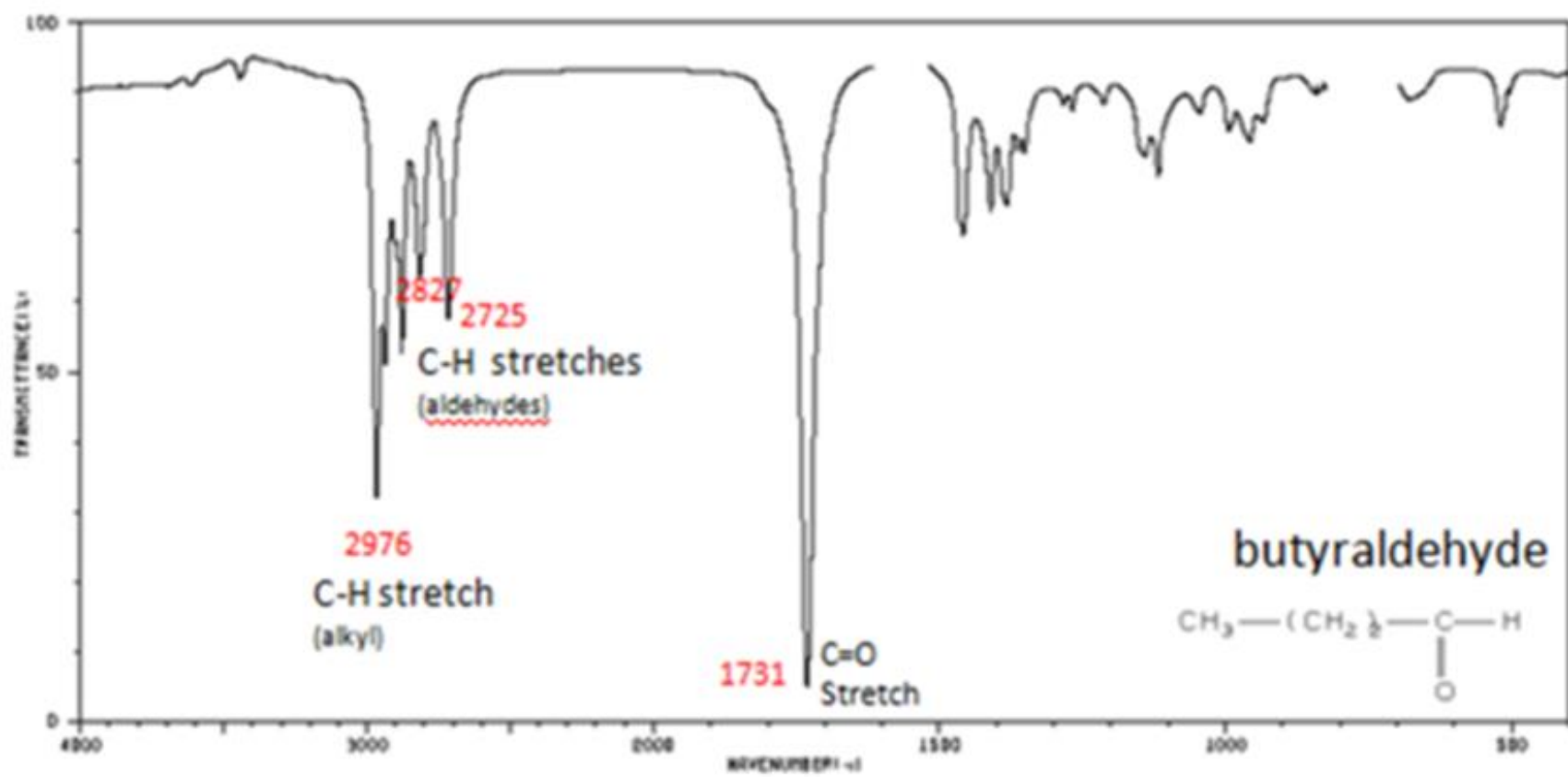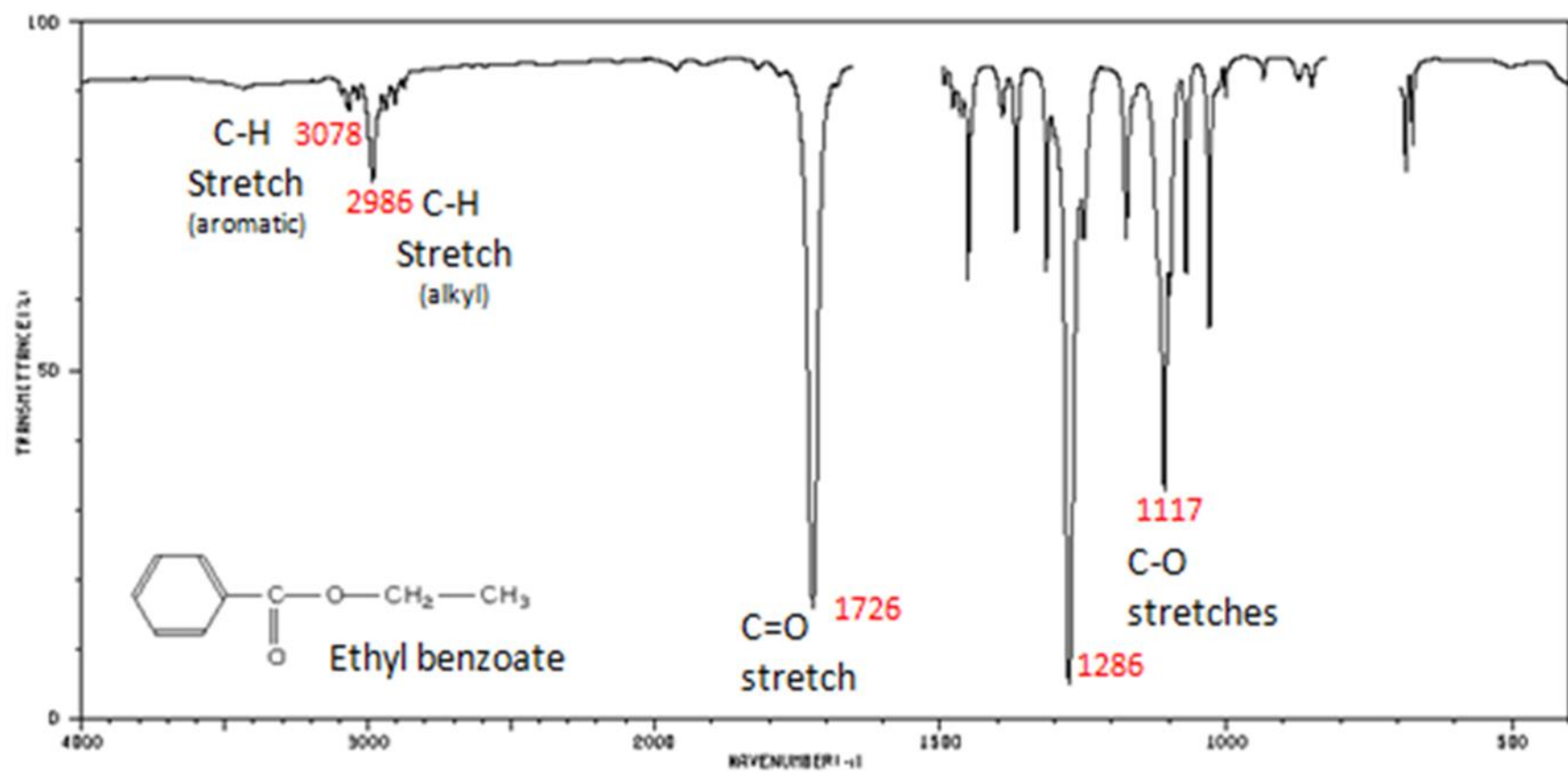
Indicate the expected IR bands for the following compound:
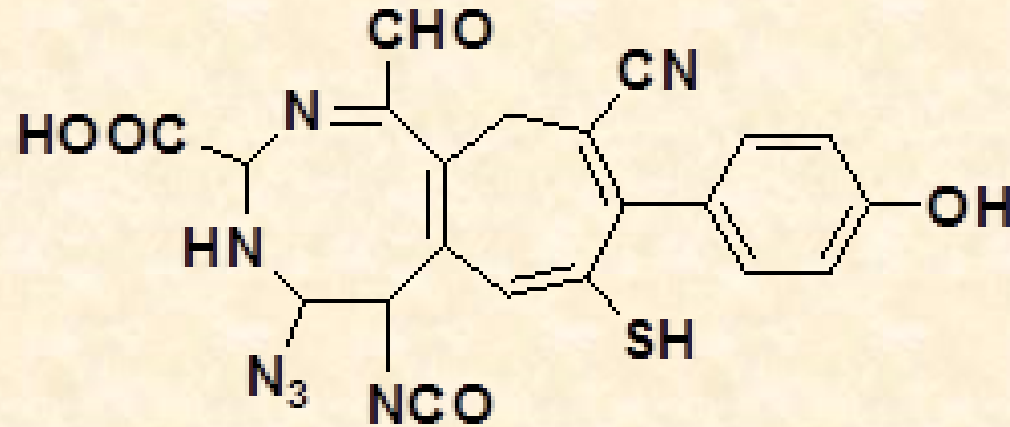
The Answer:
-CN   2220 cm-1, NH   3350-3310 cm-1,   C=O (COOH) 1760 cm-1, carboxylic -OH   2500-3500 cm-1,   -SH   2600-2550 cm-1, -CHO   2700 cm-1, 1720 cm-1, CH 2980, 2890 cm-1, N3 2160-2120 cm-1, NCO 2275-2250 cm-1 , C=N 1620 cm-1, OH 3610 cm-1, CH aromatic 3030 cm-1.

Polynuclear aromatic hydrocarbons (PAHs)

اعداد: ا.م.د. همت محمد دردير قليعي

كلية العلوم

قسم الكيمياء

العام الجامعي

2023/2022

بيانات الكتاب

الكلية: العلوم

الفرقه: الثالثه

التخصص: Chemistry

تاريخ النشر: 2023

Content

Introduction

Polynuclear aromatic hydrocarbons (PAHs) contain two or more aromatic rings, each pair of which shares two ring carbon atoms. Naphthalene, anthracene, and phenanthrene, the most common PAHs, and substances derived from them are found in coal tar and high-boiling petroleum residues. At one time, naphthalene was used as a moth repellent and insecticide in protecting woolens and furs, but its use has decreased due to the introduction of chlorinated hydrocarbons such as p-dichlorobenzene. Also found in coal tar are lesser amounts of benzo[a]pyrene. This compound is found as well in the exhausts of gasoline-powered internal combustion engines (for example, automobile engines) and in cigarette smoke. Benzo[a]pyrene is a very potent carcinogen and mutagen.

A polycyclic aromatic hydrocarbon (PAH) is a hydrocarbon—a chemical compound containing only carbon and hydrogen—that is composed of multiple aromatic rings. The group is a major subset of the aromatic hydrocarbons. The simplest of such chemicals are naphthalene, having two aromatic rings, and the three-ring compounds anthracene and phenanthrene. The terms polyaromatic hydrocarbon or polynuclear aromatic hydrocarbon are also used for this concept. PAHs are uncharged, non-polar molecules, with distinctive properties due in part to the delocalized electrons in their aromatic rings. Many of them are found in coal and in oil deposits, and are also produced by the thermal decomposition of organic matter—for example, in engines and incinerators or when biomass burns in forest fires.

Polycyclic aromatic hydrocarbons are discussed as possible starting materials for abiotic syntheses of materials required by the earliest forms of life.

Classification of PAHs

PAHs

Benzenoid

Nonbenzenoid

Isolated

Biphenyl

Fused

Linear

Anthracene

Angular
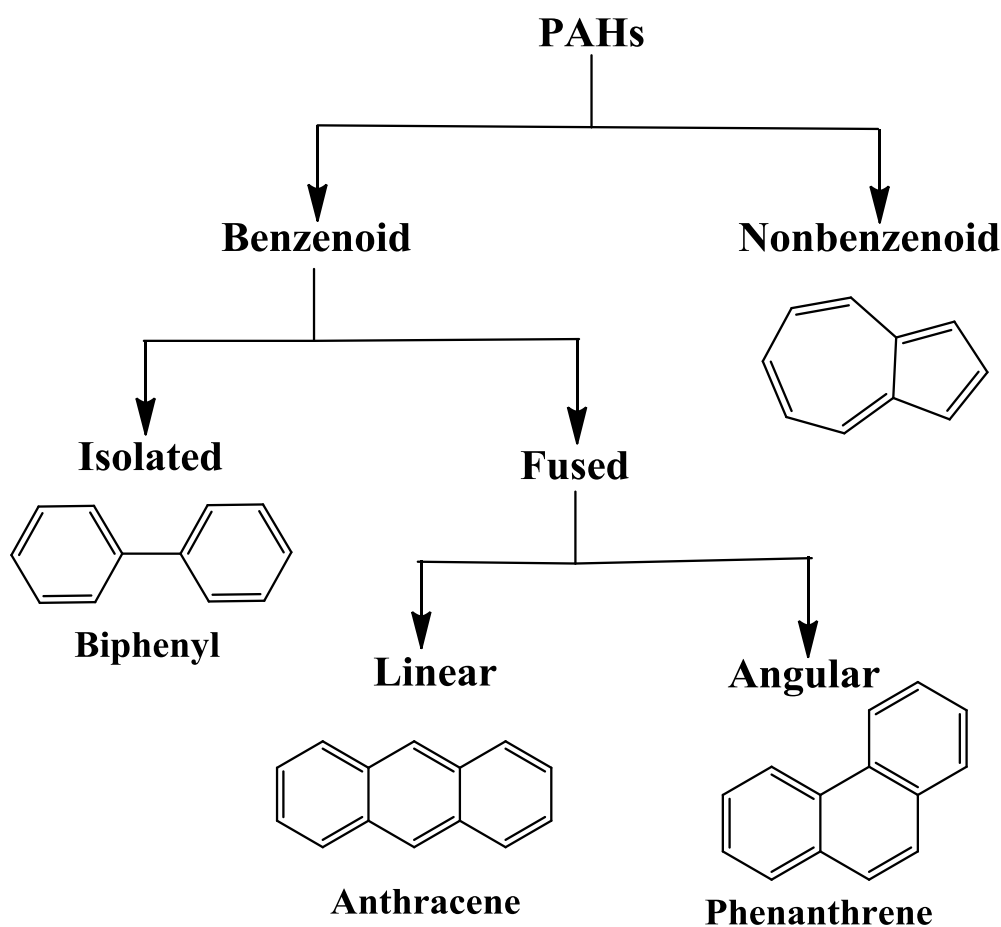
Phenanthrene

➤ There are two different ways to join three rings together, forming anthracene and phenanthrene.

➤ As the number of fused rings increases, the number of resonance structures increases. Naphthalene is a hybrid of three resonance structures whereas benzene is a hybrid of two.

Requirements for any compound to be aromatic:

1- Cyclic

2- Planner

3- All atoms must be SP^2

4- All double bonds must be conjugated

5- Obey Huckle's rule which states that any aromatic compound must contain $4n+2$ π electrons where n 0,1,2,3,…

Biphenyl and atropisomerism

Atropisomerism is stereoisomerism results from restricted rotation around single bonds (axis of chiral). An axis about it a set of atoms/groups are held in a spatial arrangement that is not superimposable on its mirror image .Axial chirality can be assigned by using Newman projection along the axis of hindered rotation. Use Cahn-Ingold-Prelog priority rules to assign the substituents

P = Clockwise
M = Counter clockwise
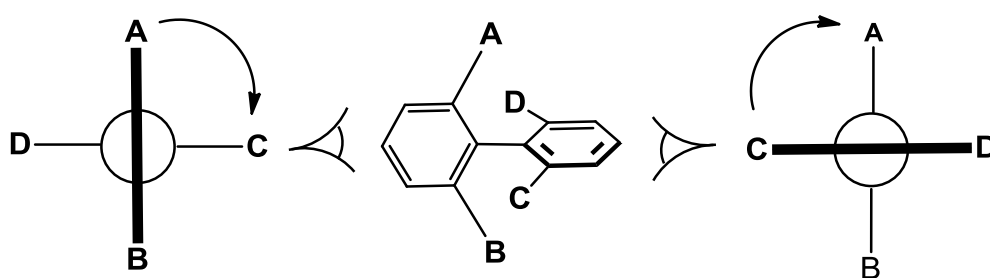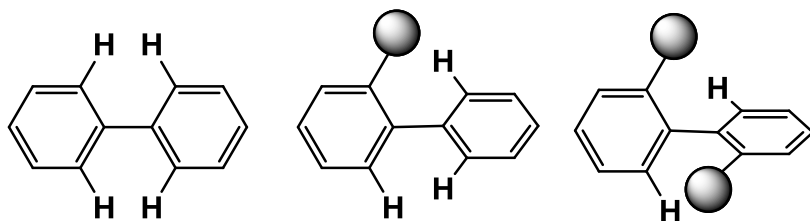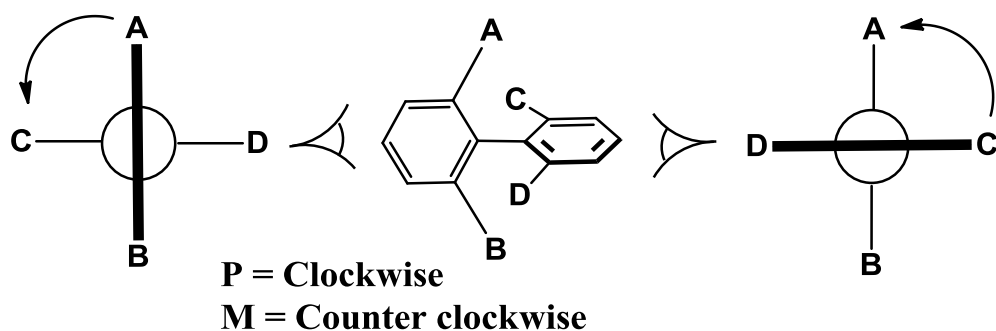
Atropisomerism in nature

vancomycin (**1**)

9
(*M*)-Murrastifoline-F

8
(*P*)-(+)-Kotanin
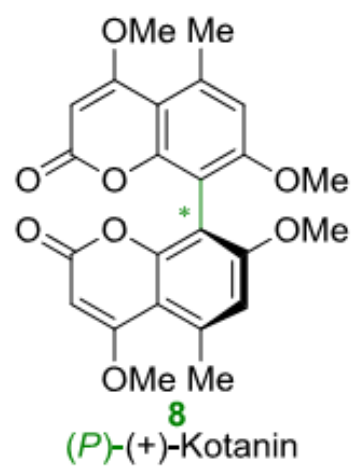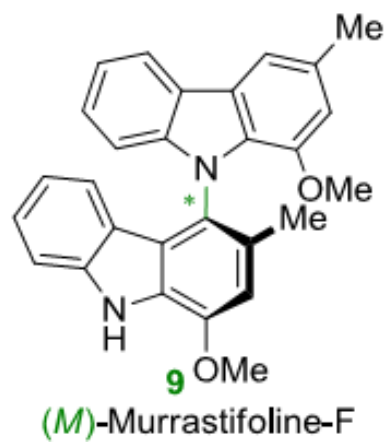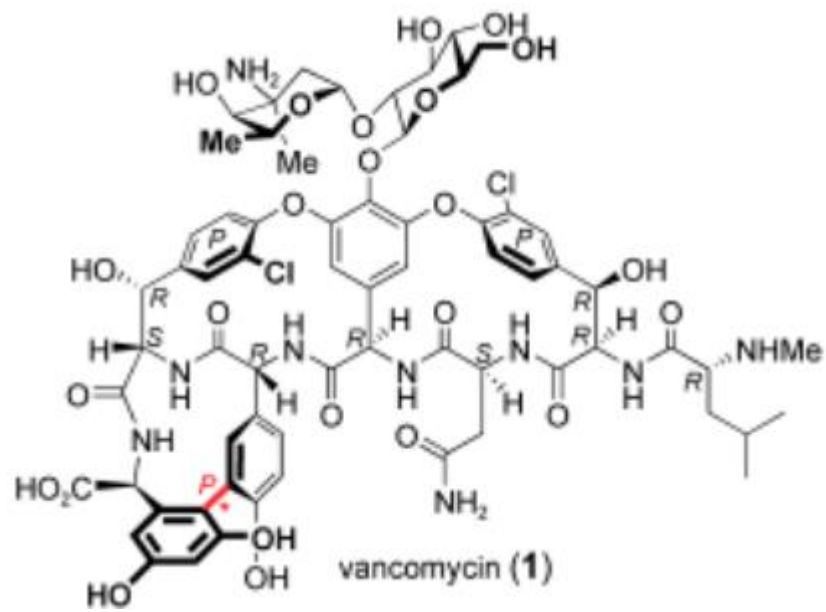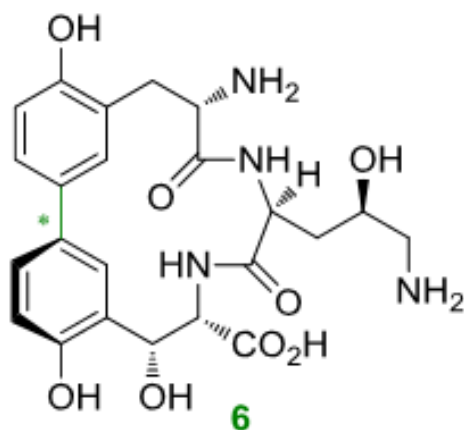
(M)-Biphenomycin A

Biphenyl

Nomenclature
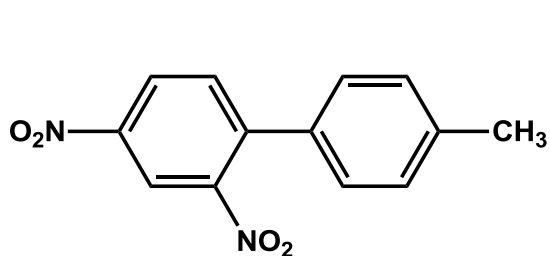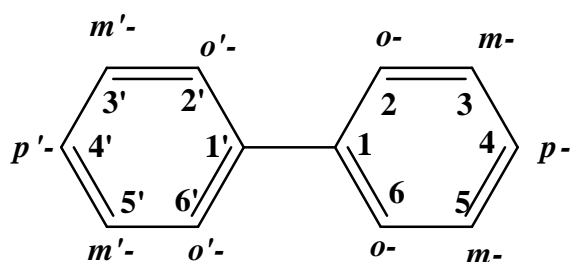
4'-methyl-2,4-dinitrobiphenyl
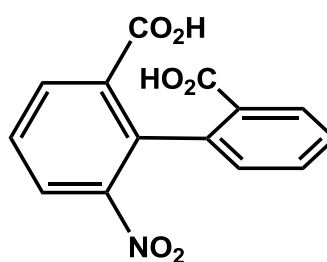
6-nitro-2,2'-biphenyldicarboxylic acid

Preparation methods

1- By Fittig's Reaction

Ionic Mechanism

S_NAr
Nucleophilic Aromatic
Substitution

+ NaBr

Free Radical Mechanism

heterolytic cleavage

Na

+ NaBr

Na

S_NAr

+ NaBr
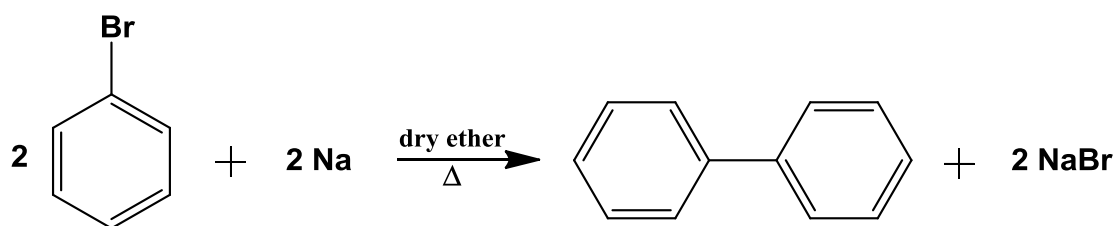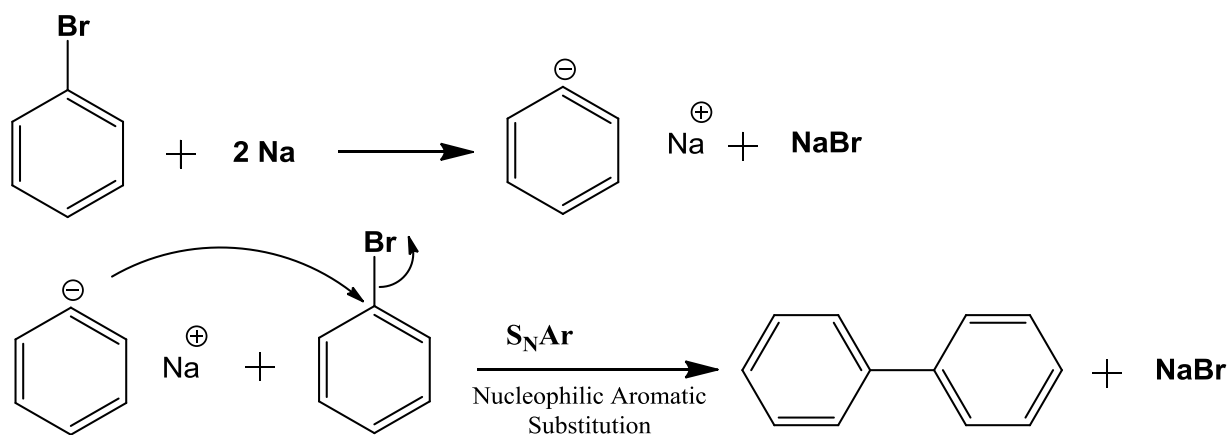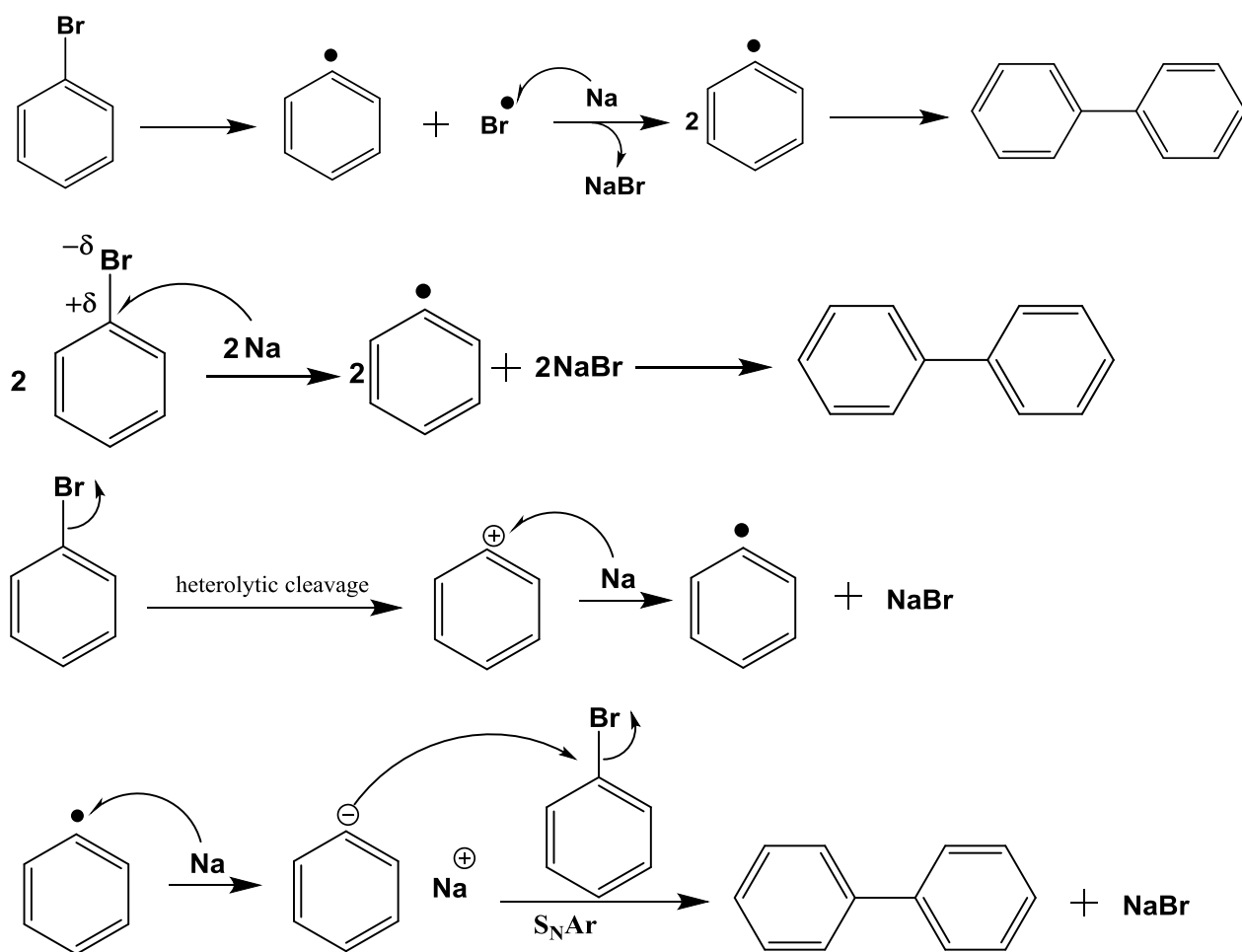
2-Alumann synthesis

+ 2CuI
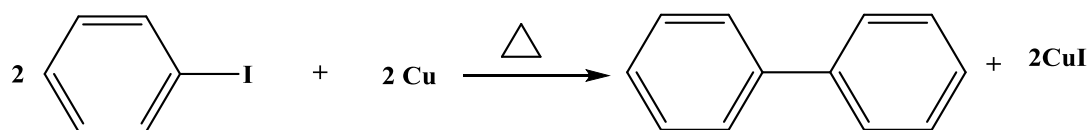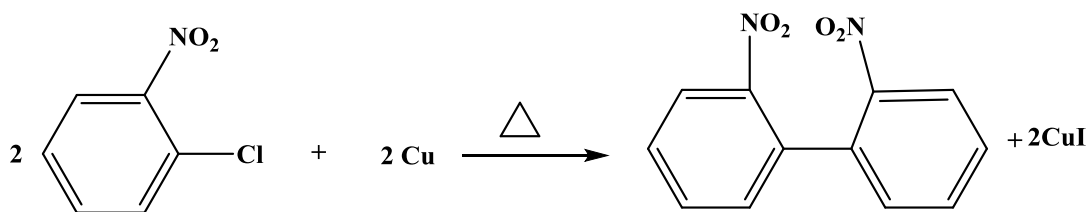
3-From Grinuard reaction
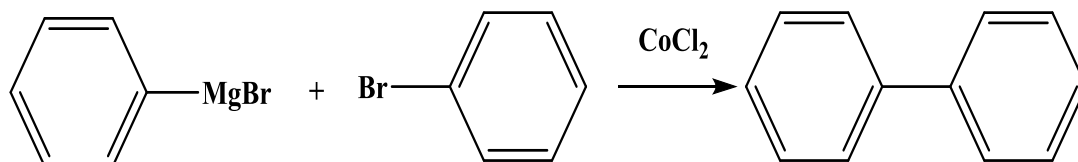
4-From Benzedine
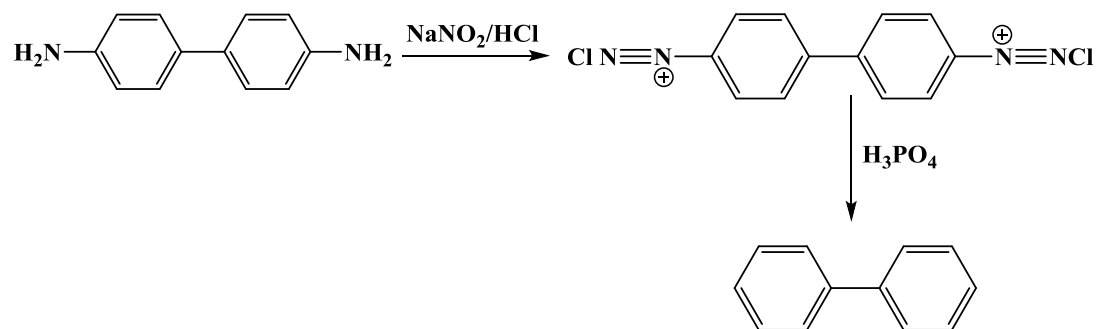
Chemical reactions

Electrophilic Substitution

Nitration
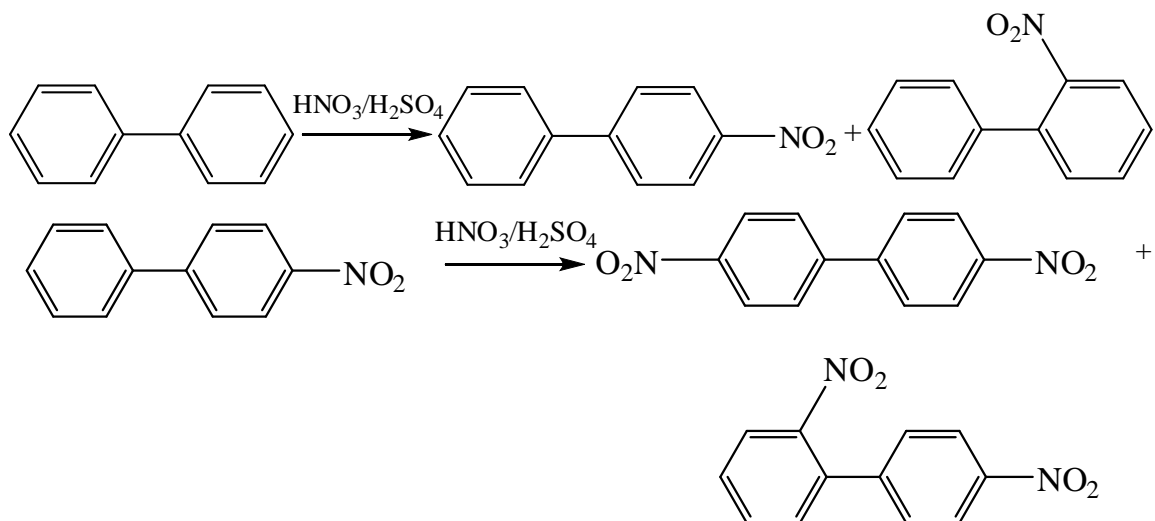
Benzidine
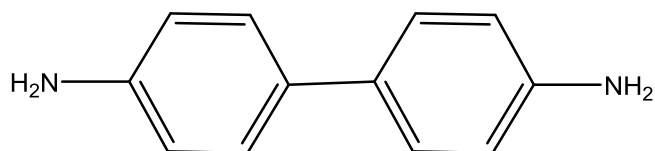
Benzedine

Synthesis

1- Benzedine rearrangement
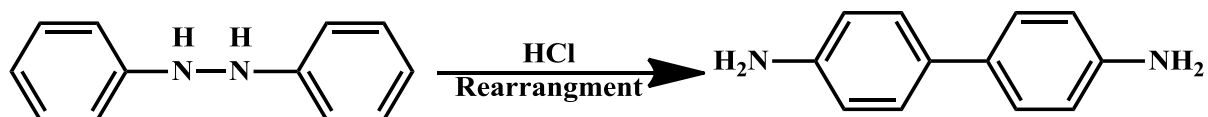
Mechanism
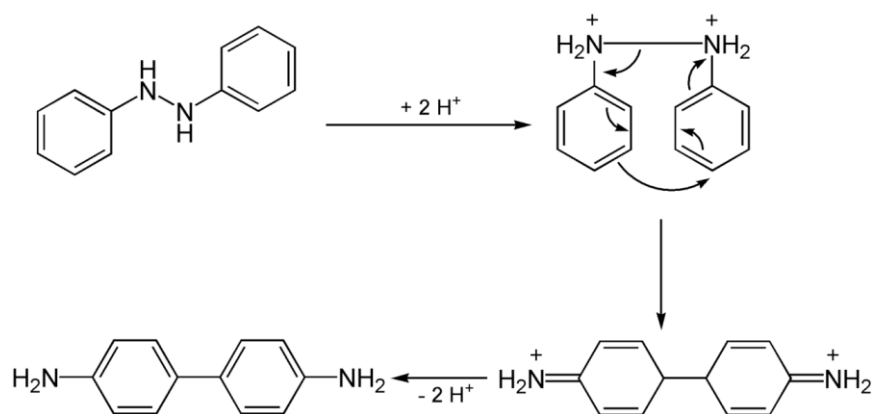
2- Ullmann's Reaction
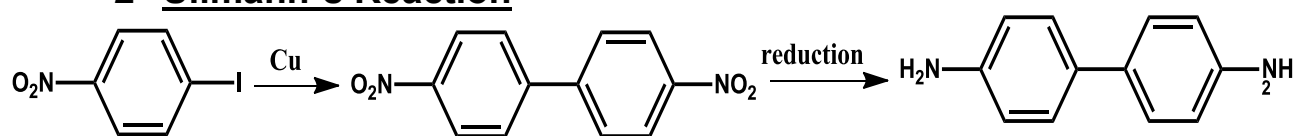
Diphenic acid
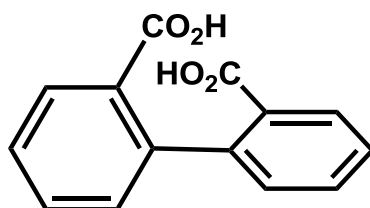
Diphenic acid (biphenyl-2,2'-dicarboxylic acid)

Synthesis (a) from phenanthraquinone

phenanthraquinone
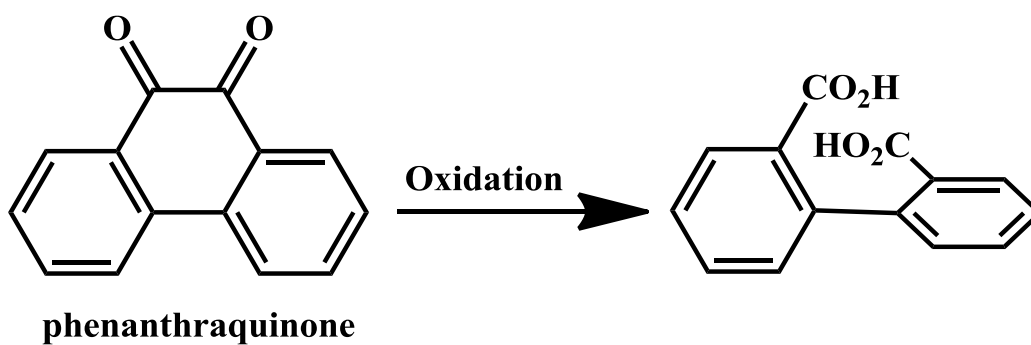
b) Ullmann's Reaction

3
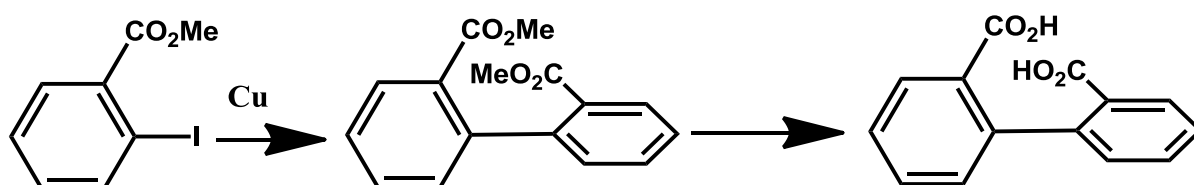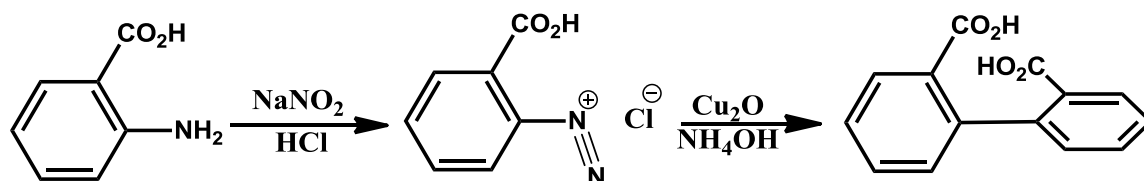
c) from anthranilic acid
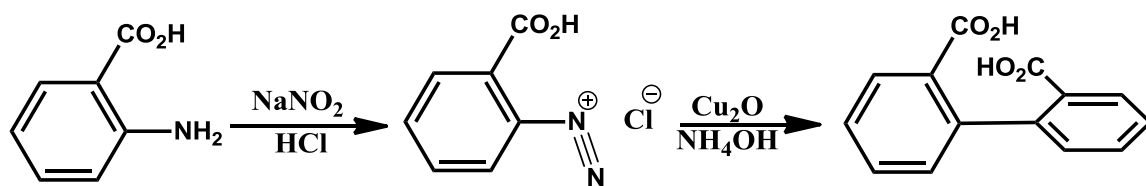
Reactions of diphenic acid

9-fluorenone-4-carboxylic acid

diphenic anhydride
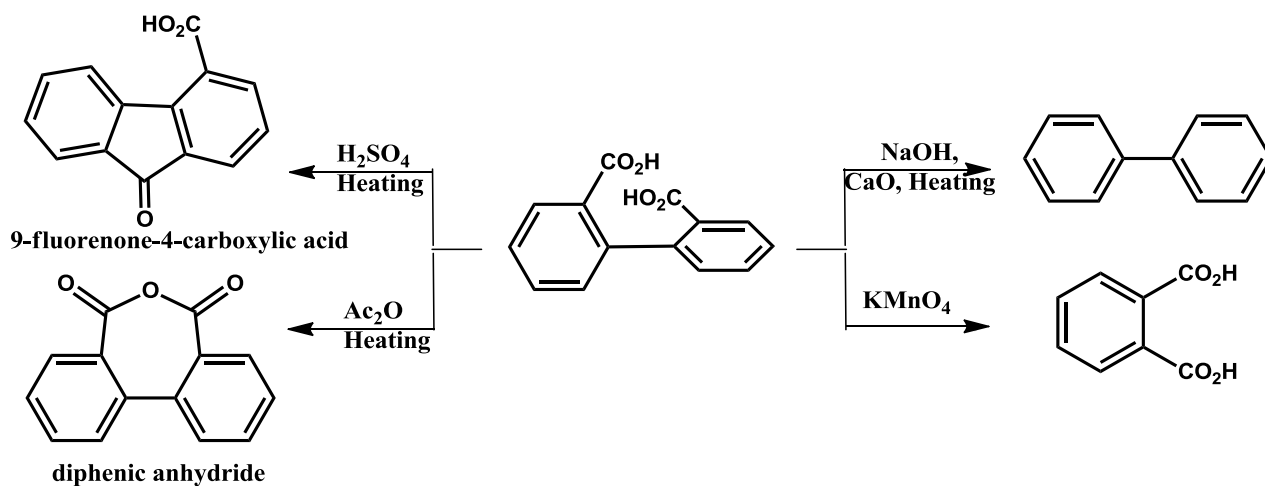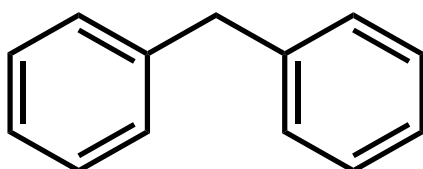
Diphenylmethane

Preparations

(1) Friedel- Craft᾽s reaction
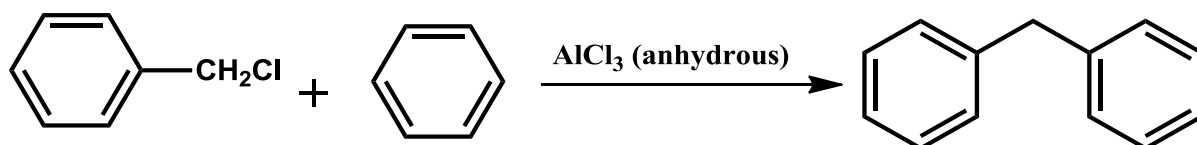
2) Condensation of benzen with formaldehyde

$$2 \quad \text{(benzene)} \xrightarrow[\text{Conc. } H_2SO_4]{CH_2O} \text{(diphenylmethane)}$$
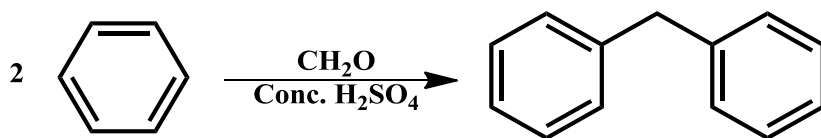
(3) Reduction of benzophenone

$$\text{(benzophenone)} \xrightarrow{HI, P} \text{(diphenylmethane)}$$
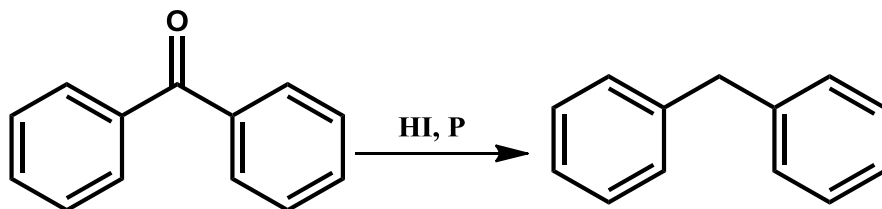
Reactions of diphenylmethane

1-Nitration

$$\text{(diphenylmethane)} \xrightarrow[\text{Conc. } H_2SO_4]{\text{Conc. } HNO_3} \text{(4-nitrodiphenylmethane)} \xrightarrow[\text{Conc. } H_2SO_4]{\text{Conc. } HNO_3} \text{(4,4'-dinitrodiphenylmethane)}$$

2-Bromination

$$\text{(diphenylmethane)} \xrightarrow{Br_2} \text{(bromodiphenylmethane)}$$

3-Oxidation

$$\text{(diphenylmethane)} \xrightarrow{H_2Cr_2O_7} \text{(benzophenone)}$$

4-Cyclization

red hot tube

Fluorene
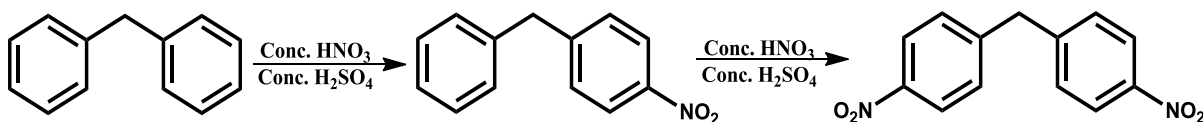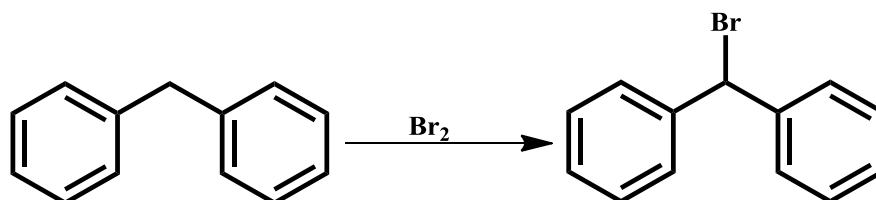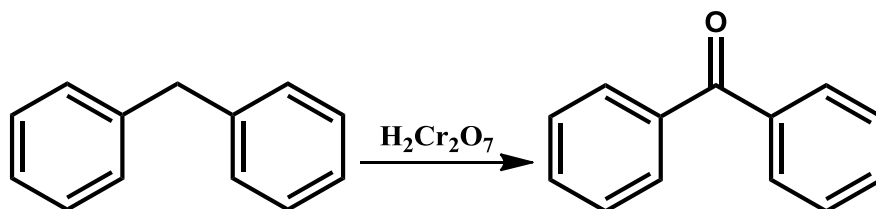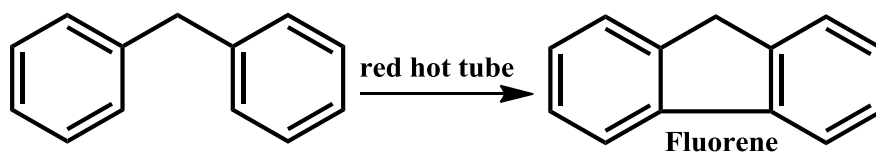
1,2-Diphenylethane

Preparation methods

(1) Friedel Crafts Reaction

2 + Cl — CH_2 — CH_2 — Cl $\xrightarrow{\text{AlCl}_3 \text{ (anhydrous)}}$

(2) Wurtz Reaction

2 —CH₂Cl $\xrightarrow{\text{Na}}$
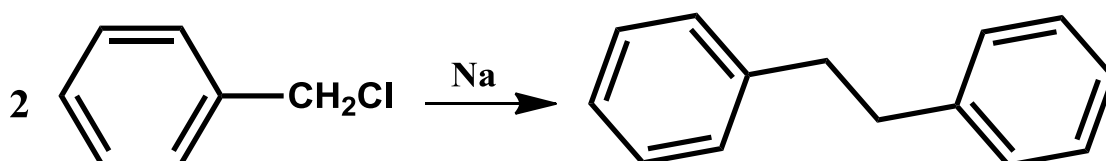
Chemical Reactions

1- Oxidation

$\xrightarrow{\text{KMnO}_4}$ 2 —COOH

Stilbene (trans-Stilbene)   Isostilbene (cis-Stilbene)
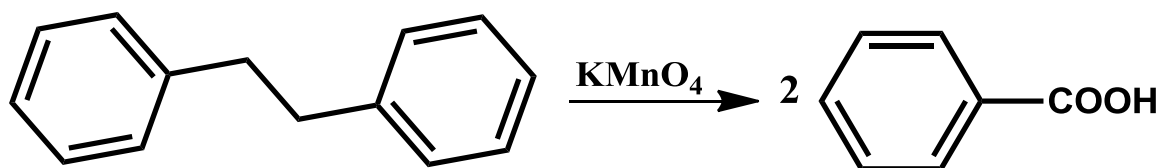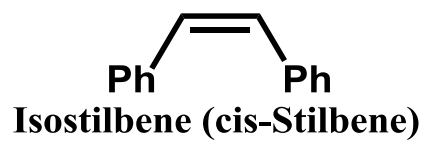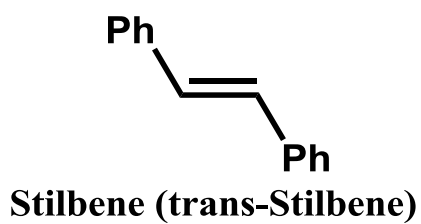
Preparation Methode

1- Wurtz reaction
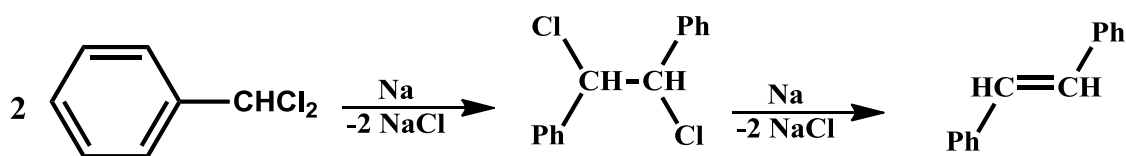
2- Grinuard reagent
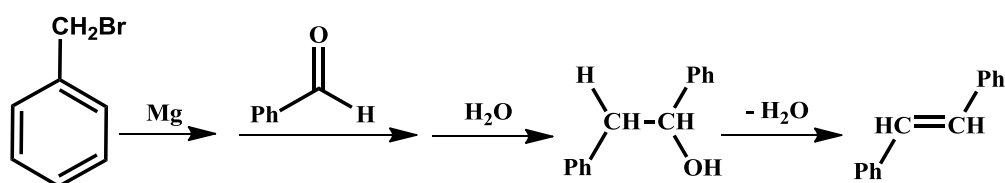
Chemical reactions

1- Reduction
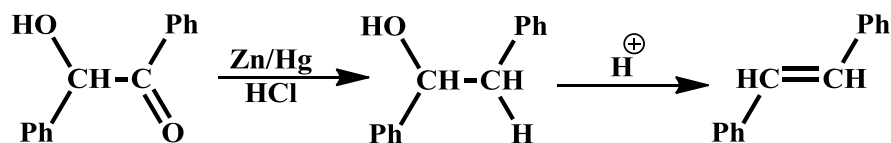
Preparation of isostilbene
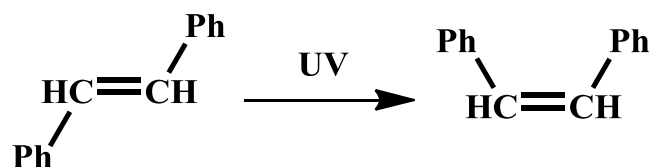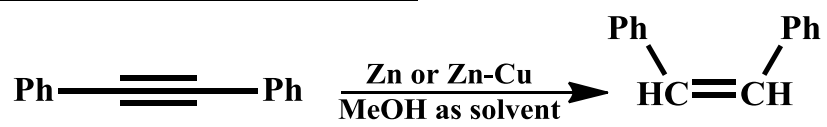
Benzoin
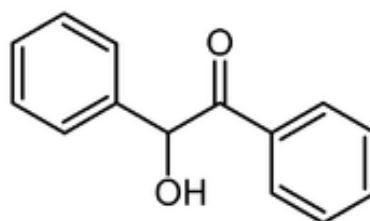
Preparation Methods
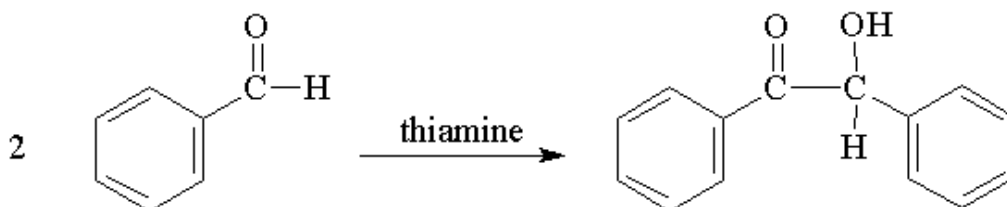
Oxidation of Benzoin
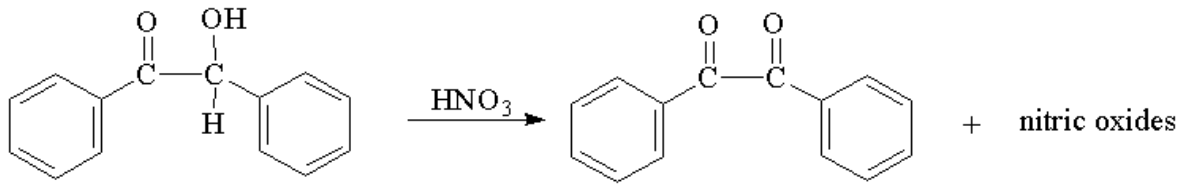
Benzil

Preparation
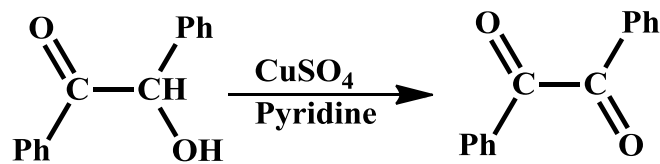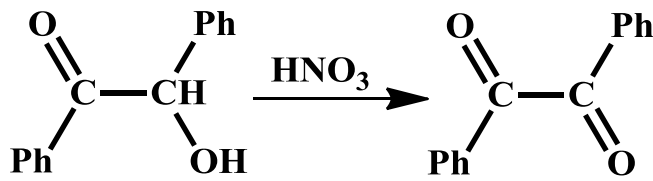
Mechanism
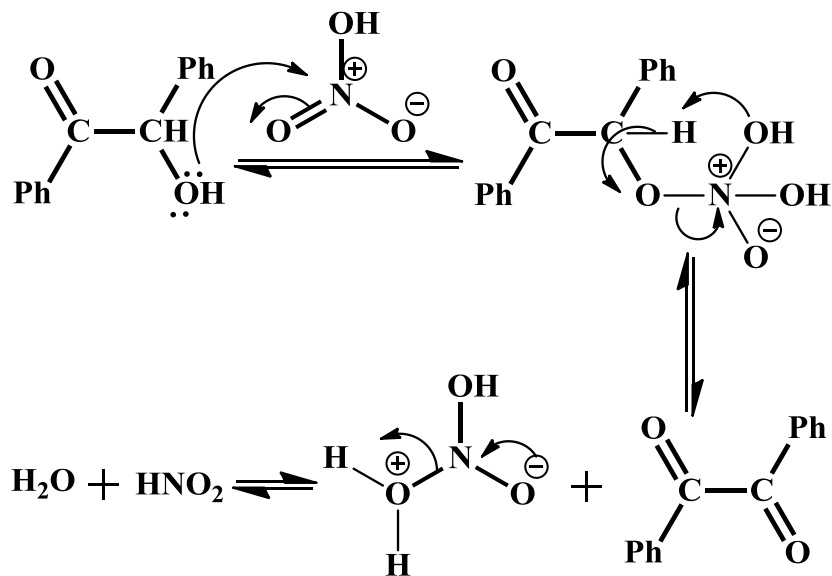
Naphthalene
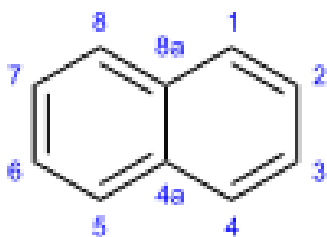
Confirmation the chemical structure
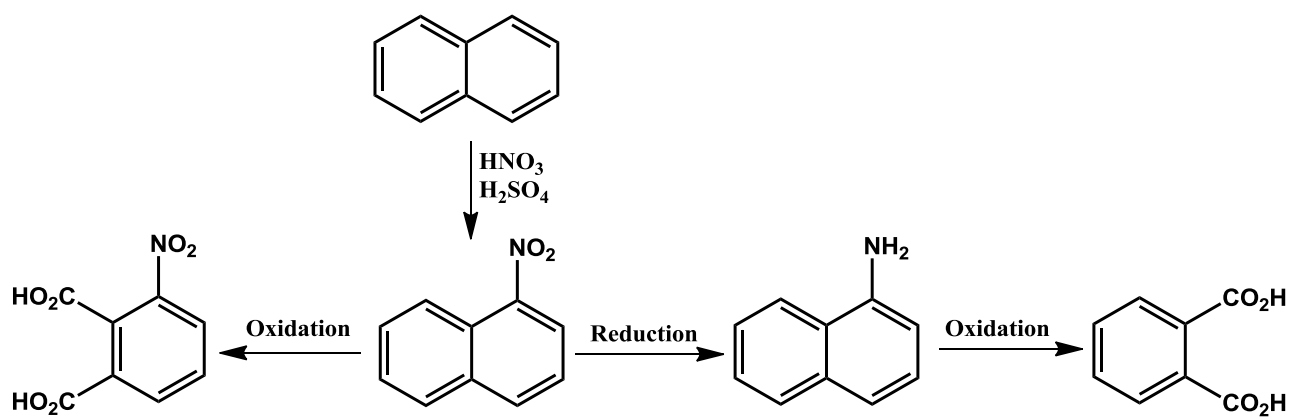
Preparation Methods

1) Using 4-phenyl-3-butenoic acid
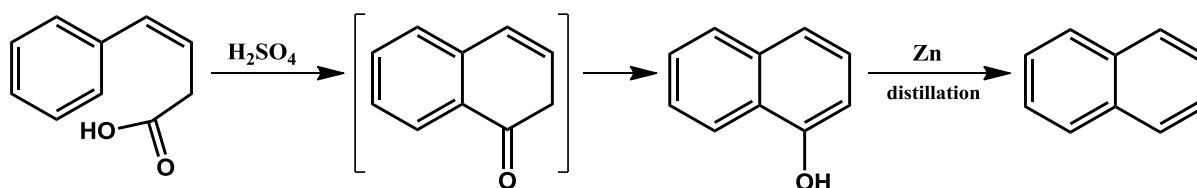
(2) Using Haworth synthesis
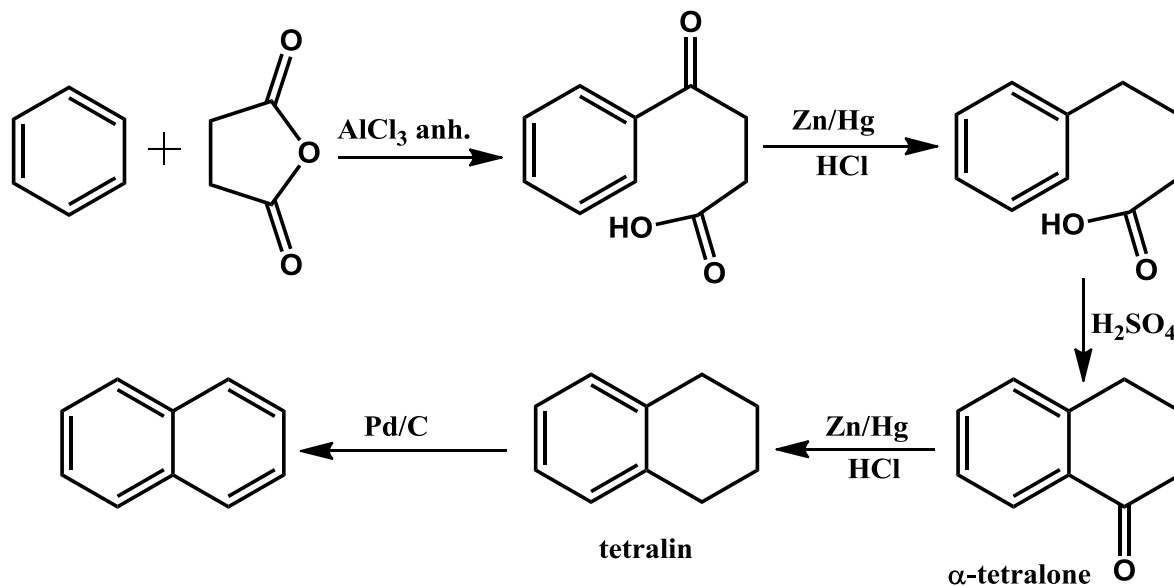
Chemical Reactions

1- Reduction
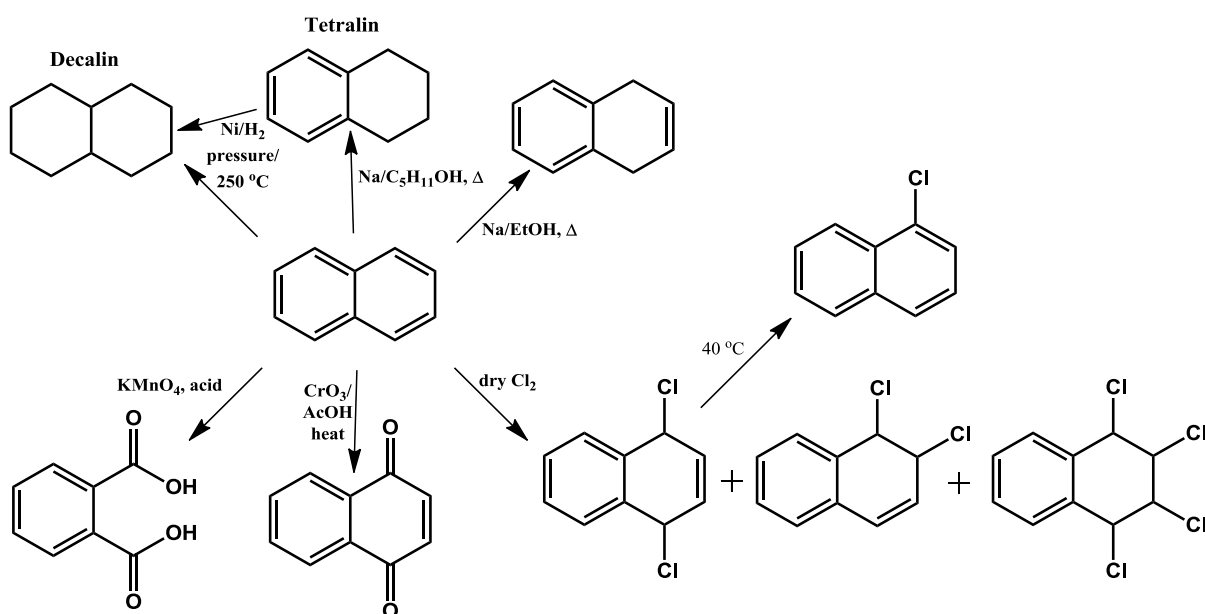
2- Oxidation
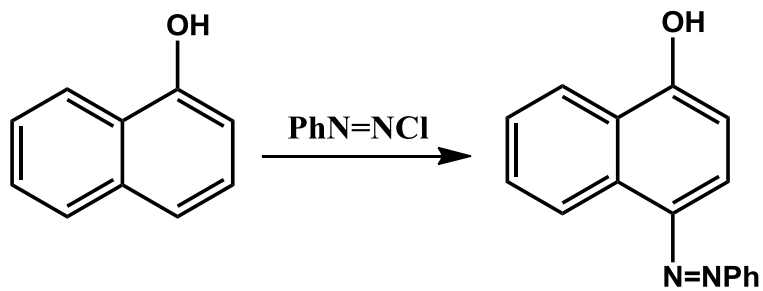## The product of oxidation depending on the oxidizing agents
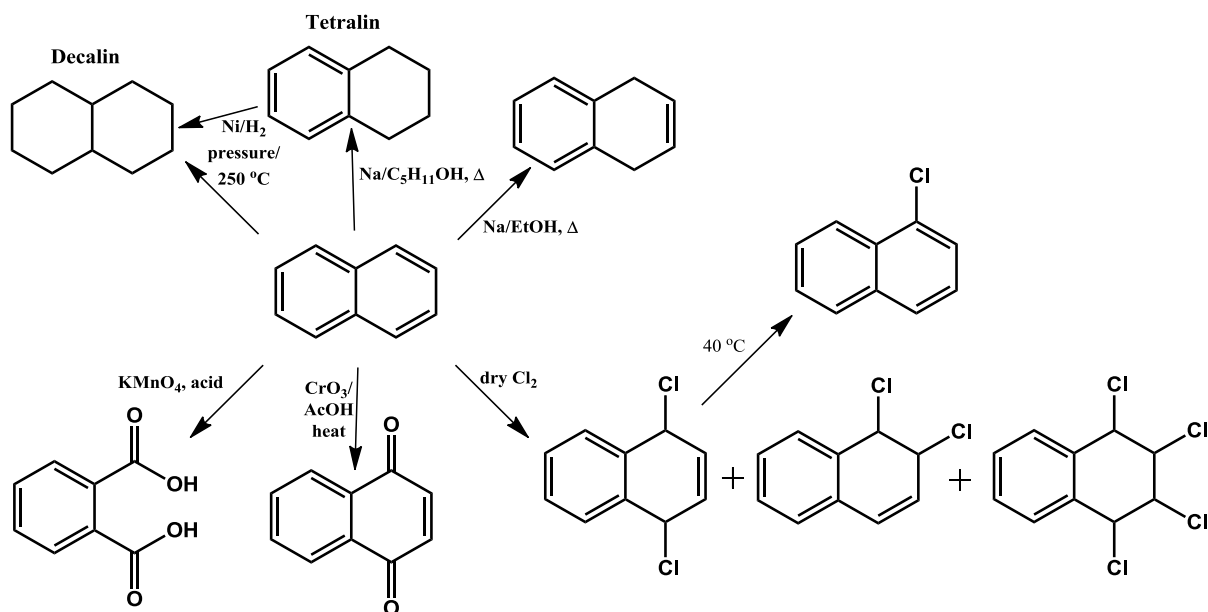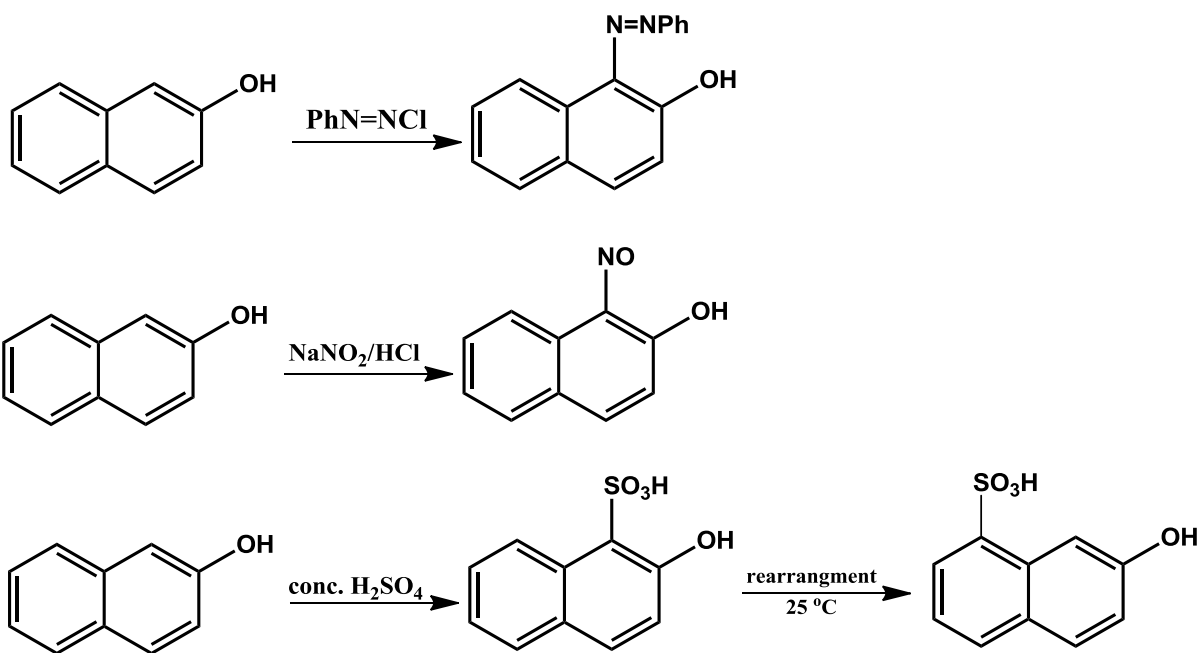
3-Friedel-Craft 's reaction
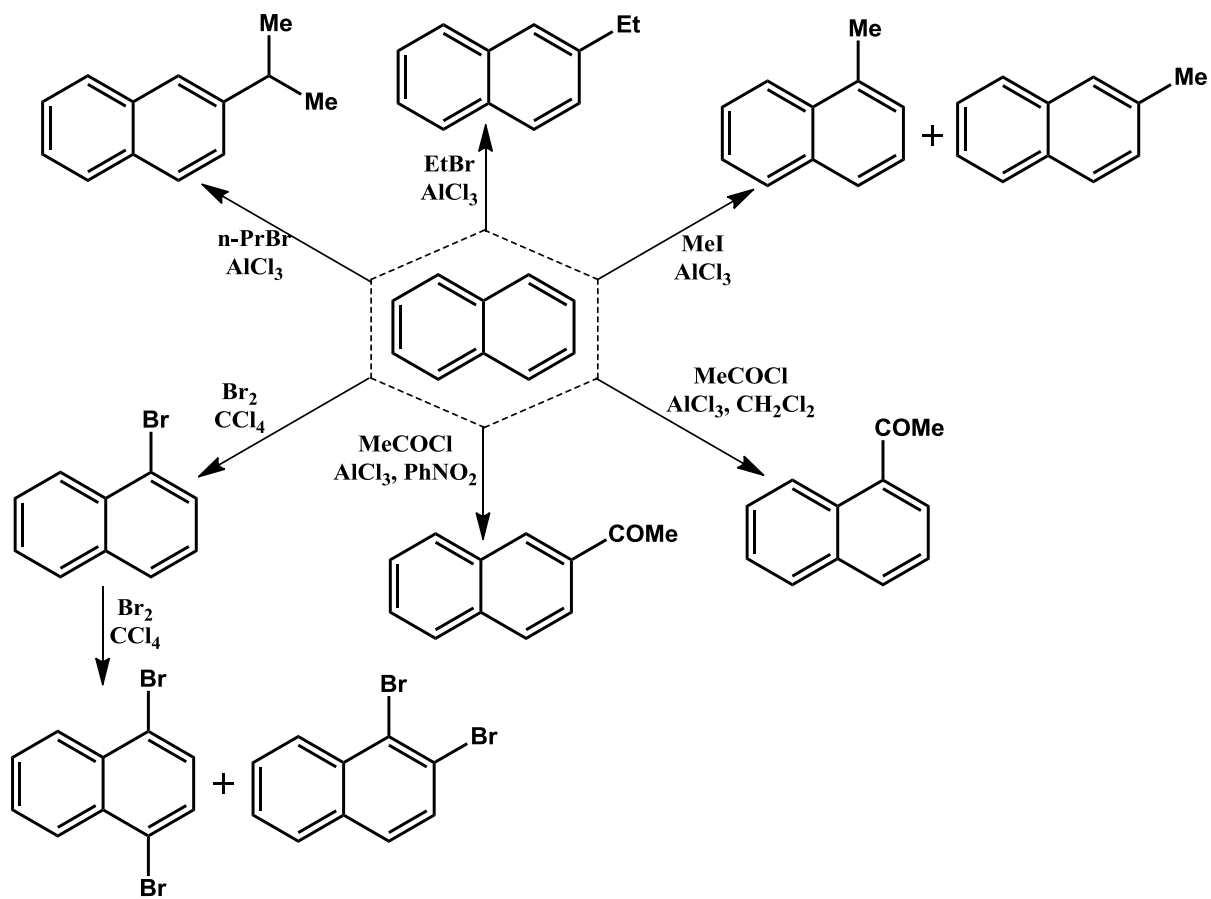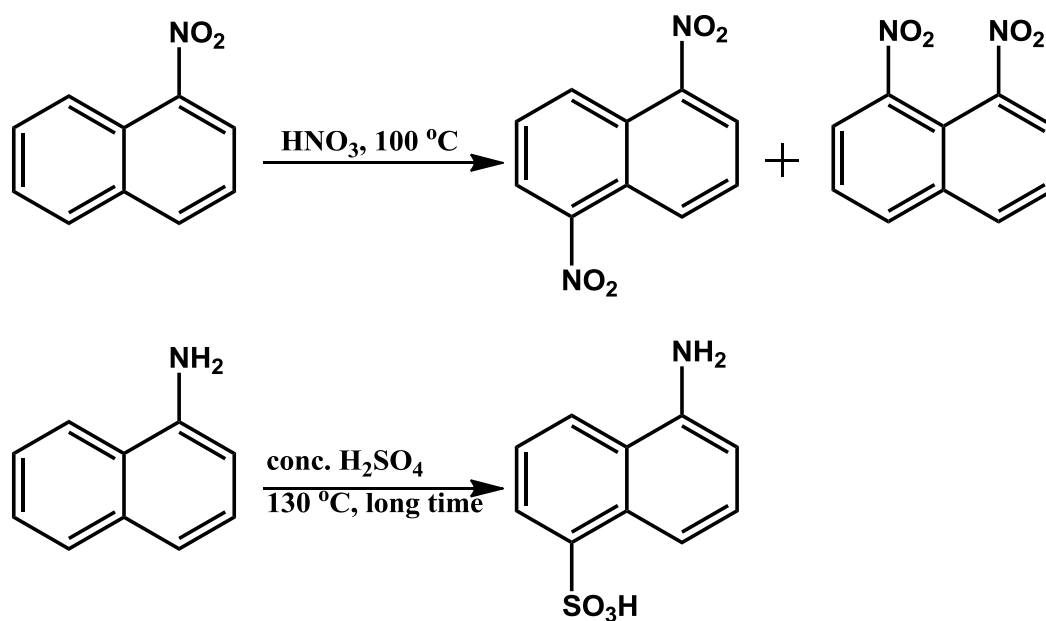
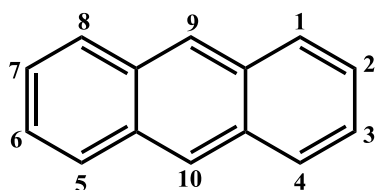## 3- Electrophilic substitution
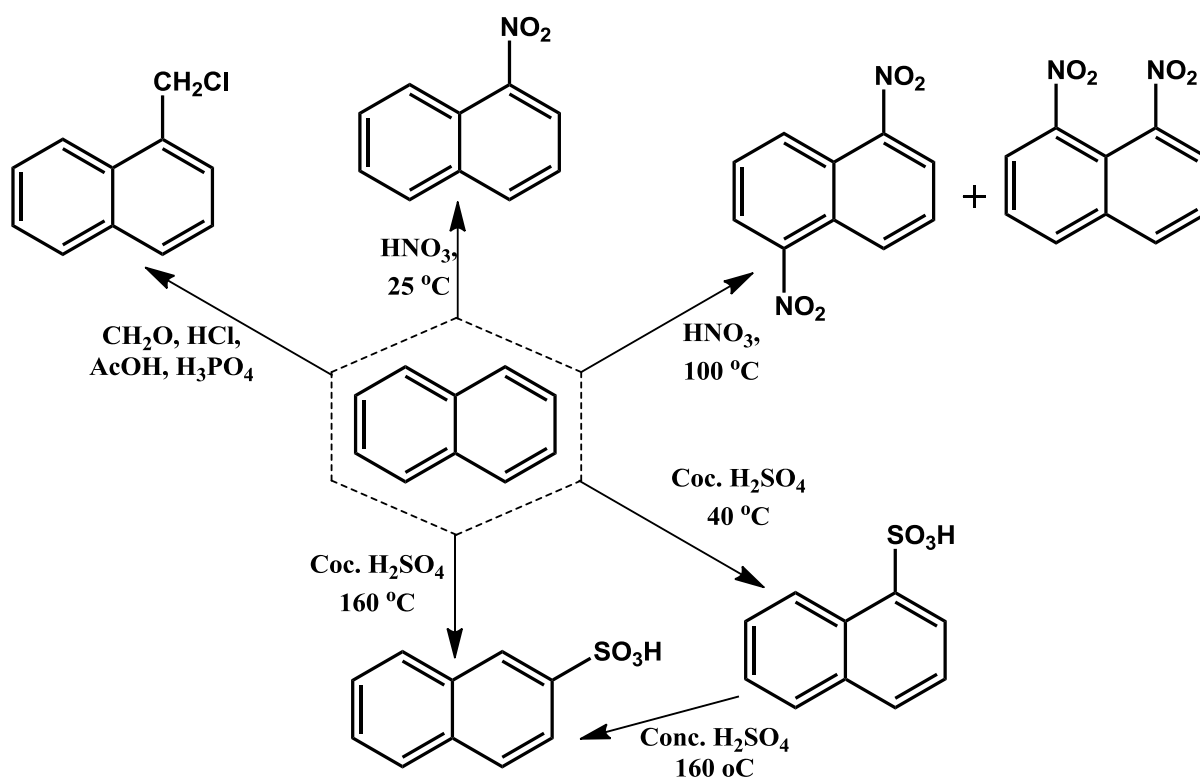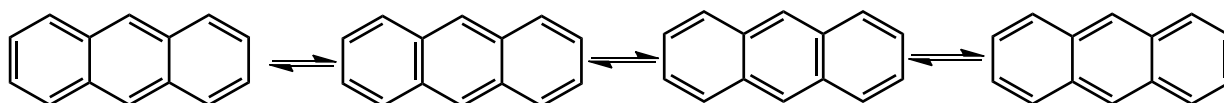
Naphthalene derivatives

Alpha-Naphthol

PhN=NCl

N=NPh
OH

NaNO$_2$/HCl

NO
OH

conc. H$_2$SO$_4$

SO$_3$H
OH

rearrangment
25 °C

SO$_3$H
OH
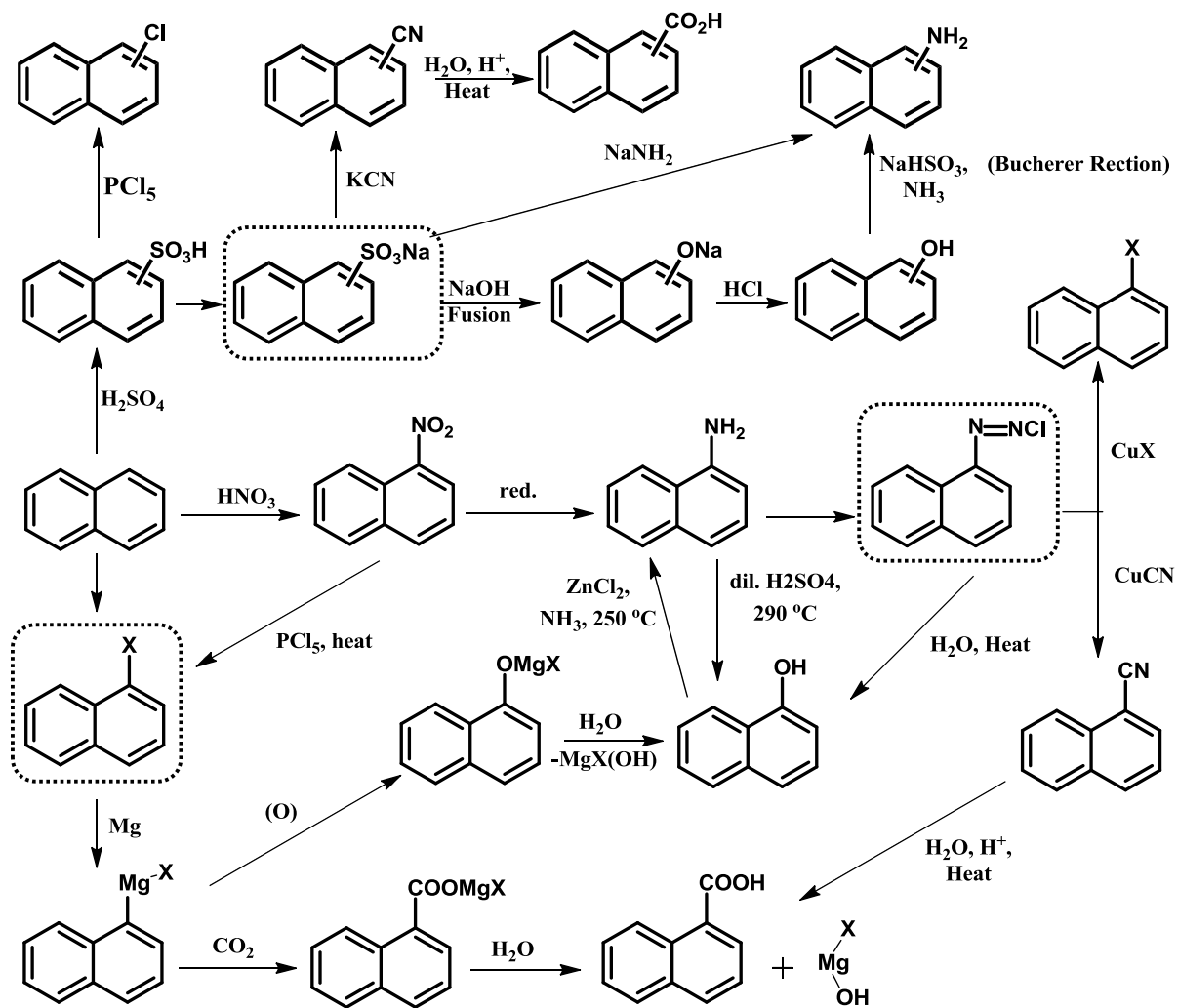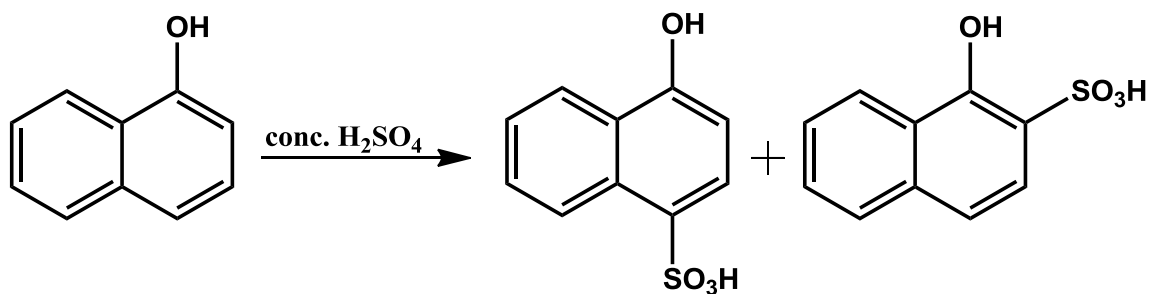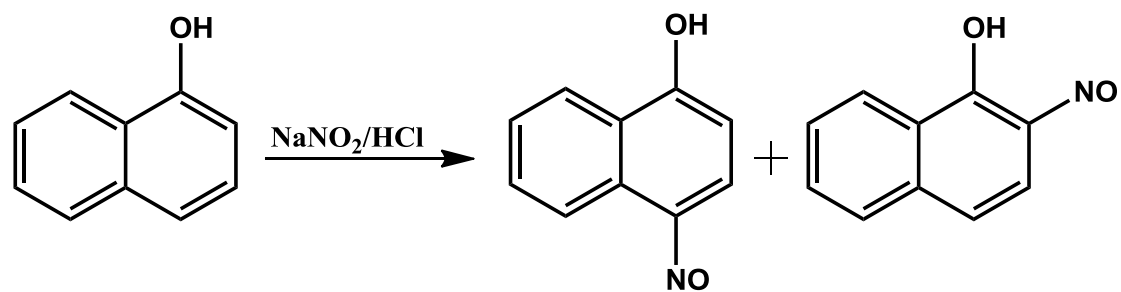
Orientation in naphthalene derivatives

NO$_2$

HNO$_3$, 100 °C

NO$_2$
NO$_2$

+

NO$_2$ NO$_2$

NH$_2$

conc. H$_2$SO$_4$
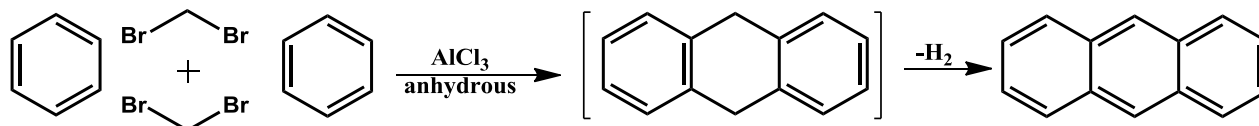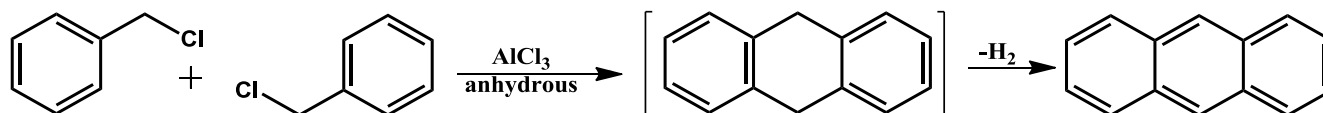130 °C, long time

NH$_2$
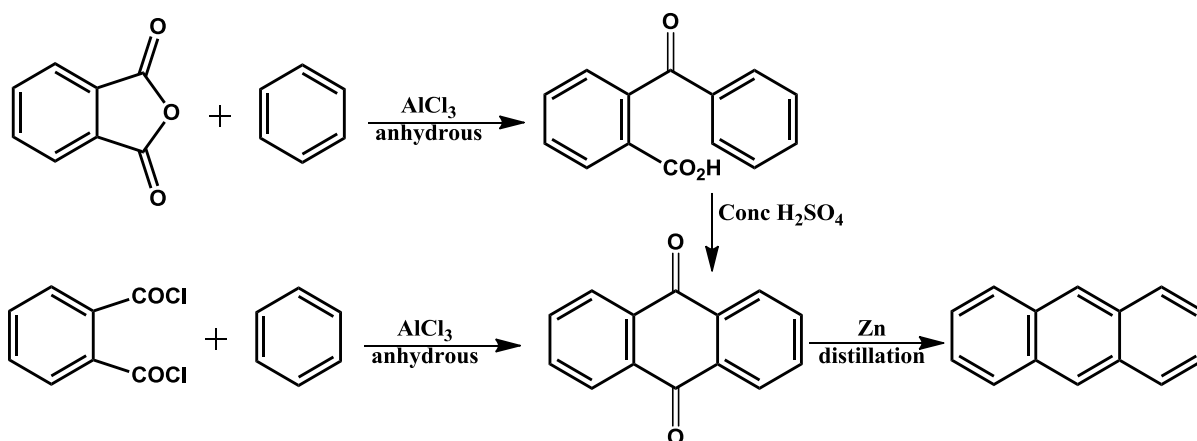SO$_3$H

Anthracene

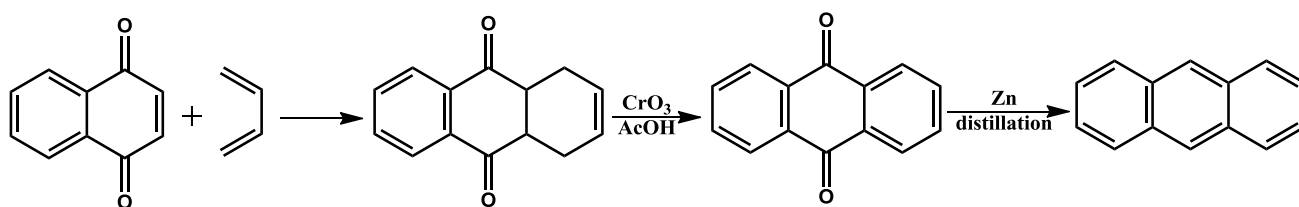
Resonance strucure of anthracene

Preparation Methods

1- Friedel-Craft ,s reaction

2- Diels- Alder, reaction

3-Wurtz-Fittig, reaction
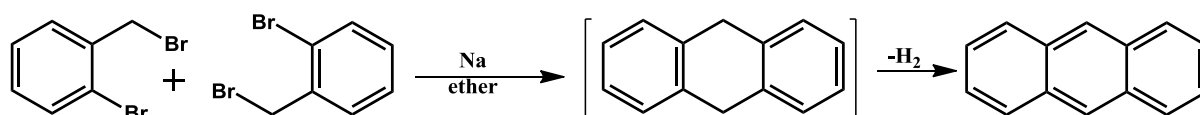
Chemical reaction of anthracene

Excess conc. H₂SO₄ low temperature → 1,8-disubstituted anthracene disulfonic acid

Conc. H₂SO₄ low temperature → anthracene-1-sulfonic acid + anthracene-2-sulfonic acid

Conc. H₂SO₄ high temperature → anthracene-2-sulfonic acid

Excess conc. H₂SO₄ high temperature → 2,6-anthracene disulfonic acid

Na/*i*-PrOH → 9,10-dihydroanthracene

Heating or Conc. H₂SO₄ ←

Conc. HNO₃/ Ac₂O, rt → 9-nitroanthracene + 9,10-dinitroanthracene
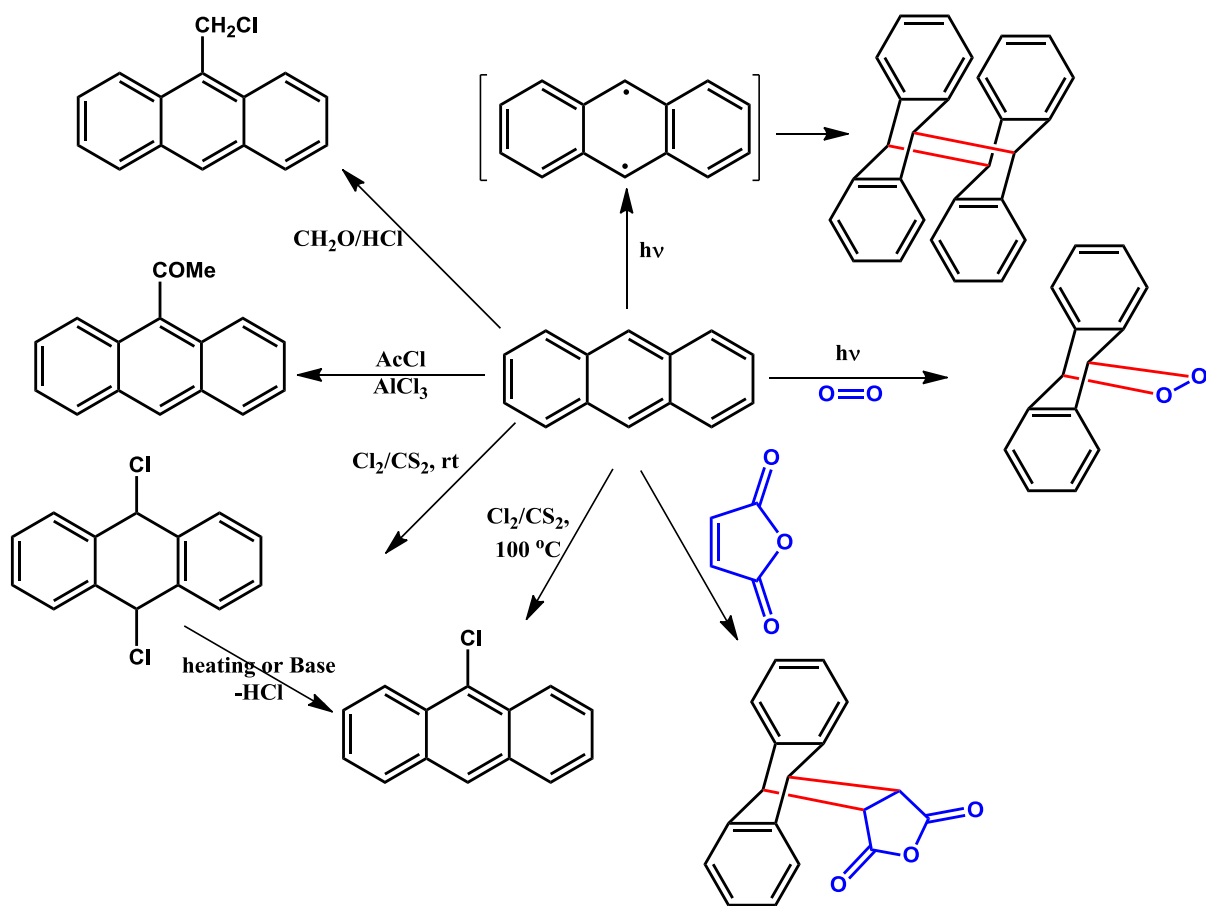
المراجع

Nomenclature of Organic Chemistry : IUPAC Recommendations and Preferred Names 2013 (Blue Book). Cambridge: The Royal Society of Chemistry. 2014 صفحات 13، 35، 204، 207، 221–222، 302، 457، 461، 469، 601، 650. doi:10.1039/9781849733069-FP001. ISBN 978-0-85404-182-4.

PubChem CID): https://pubchem.ncbi.nlm.nih.gov/compound/931) " naphthalene

PubChem CID): https://pubchem.ncbi.nlm.nih.gov/compound/93) "