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CHEMISTRY

**PAPER No. 5: Organic Chemistry-II
(Reaction Mechanism-1)**

MODULE No. 1: Types of Organic Reactions

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1. Learning Outcomes

After studying this module, you shall be able to

- Know the various types of organic reactions
- Learn the difference between each type of reaction
- Identify the reaction types depending upon reactants and conditions
- Analyze organic reactions

2. Introduction

An organic reaction is a change in structure or functional group leading to formation of a new substance. The compound undergoing a change in structure or functional group is called a reactant or substrate. The knowledge of organic reactions helps in the synthesis of useful chemical compounds such as polymers, dyes, drugs, perfumes, cosmetics, fertilizers, food preservatives.

3. Types of Organic Reactions

The organic reactions can be generally classified as substitution, addition, elimination, rearrangement, oxidation and reduction reactions.

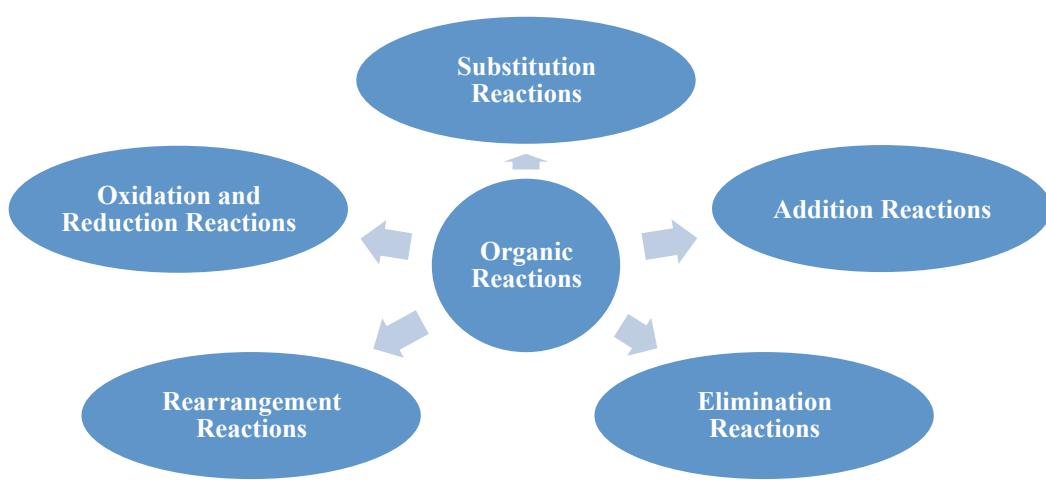
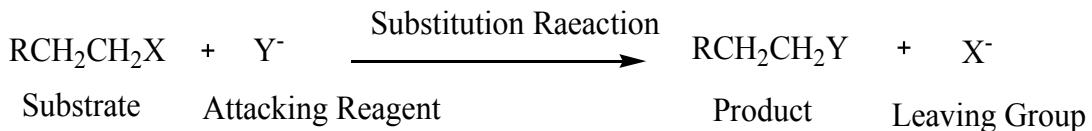


Fig 1: Types of organic reactions

3.1 Substitution Reactions

These reactions involve the displacement of an atom or a group by another atom or group.



It takes place at

- a) sp^3 hybridised carbon (alkane, haloalkane, alcohol)
- b) sp^2 hybridised carbon (benzene)

A substitution reaction can be nucleophilic, electrophilic or free radical substitution reaction.

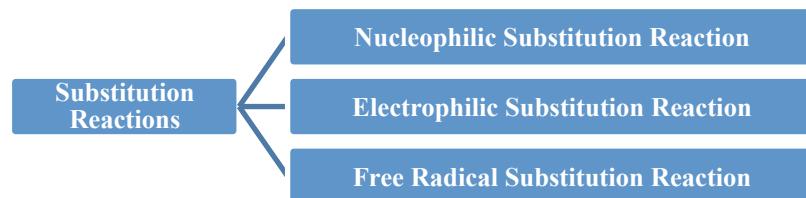


Fig 2: Types of substitution reactions

3.1.1 Nucleophilic Substitution Reactions

Attack of nucleophile at a saturated carbon atom, bearing a substituent known as leaving group results in a nucleophilic substitution reaction. The compound on which substitution takes place is called the substrate and the group that is displaced from carbon is called leaving group.

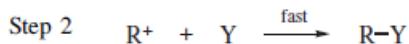


The nucleophilic reaction may follow the following pathways:

(a) Substitution nucleophilic unimolecular mechanism ($\text{S}_{\text{N}}1$)

Such reactions proceed in two steps *via* formation of a carbocation intermediate and the product obtained is a racemic mixture. For example, the hydrolysis of tertiary halides follow $\text{S}_{\text{N}}1$ pathway. The initiation step is ionization of substrate which is slow and rate determining step. The second step is a rapid reaction between the intermediate carbocation and the nucleophile.

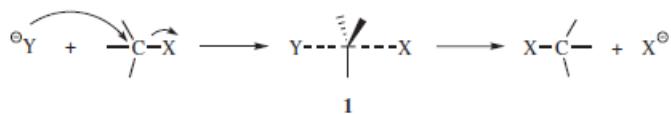
$$\text{Rate} = k [\text{RX}]$$



(b) Substitution nucleophilic bimolecular mechanism (S_N2)

Such reactions proceed in one step *via* a transition state and inversion of configuration. For example, the hydrolysis of primary halides follow S_N2 pathway. In this mechanism, there is backside attack, the nucleophile approaches the substrate from the position 180° away from the leaving group. This is a one step process with no intermediate.

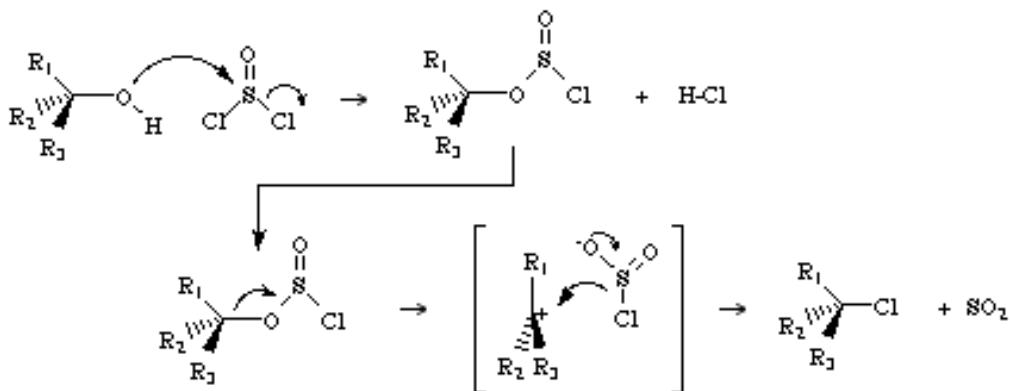
$$\text{Rate} = k [\text{RX}] [\text{Nu}]$$



(c) Substitution nucleophilic internal mechanism (S_{NI})

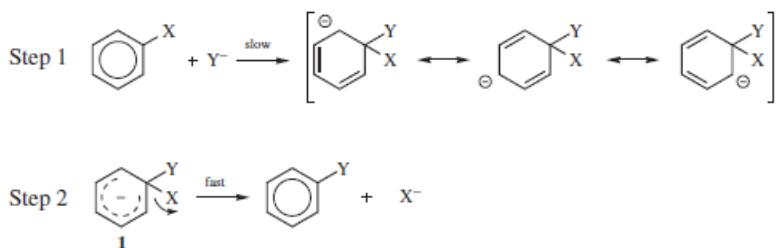
In the reaction of alcohol with thionyl chloride, displacement of hydroxyl group by chloride proceeds *via* S_{NI} mechanism. In this reaction the configuration is retained and it follows second order kinetics. In S_{NI} mechanism, part of the leaving group must be able to attack the substrate, detaching itself from the rest of the leaving group in the process.

$$\text{Rate} = k [\text{ROH}] [\text{SOCl}_2]$$



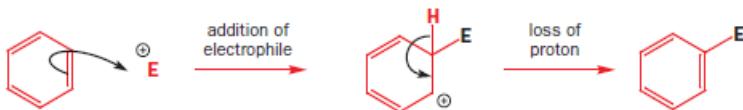
(d) Aromatic nucleophilic substitution (S_NAr)

In nucleophilic aromatic substitution a strong nucleophile replace a leaving group. The initiation step is usually, but not always, rate-determining. In general, the attacking species forms a bond with the substrate, giving an intermediate and then the leaving group departs.



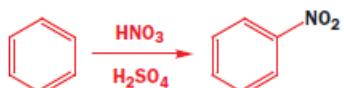
3.1.2 Electrophilic Substitution Reactions

It involves substitution in the aromatic ring by an electrophile. In the first step the electrophile is attacked by the π -electrons of the aromatic ring leading to the formation of a new carbon-electrophile bond. It is followed by loss of a proton. In these reaction, electrophile first attack to give an intermediate with positive charge, known as arenium ion and in the second step leaving group departs. This is known as arenium ion mechanism.



Examples of electrophilic substitution reactions are:

(a) Nitration: It involves a nitronium ion (NO_2^+) as an electrophile.

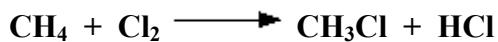


(b) Sulphonation: In this reaction sulphur trioxide (SO_3) acts as an electrophile.



3.1.3 Free Radical Substitution Reactions

Such reactions begin with the formation of a free radical which substitutes a group or atom present in the reactant molecule. The reaction of methane with chlorine in the presence of light is a free radical substitution reaction.



The first step is initiation i.e free radical formation by homolytic cleavage of bonds. Second step is chain propagation and finally chain termination step

Initiation

Initiation step may happen spontaneously or may be induced by heat or light depending on the type of bond.



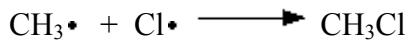
Chain Propagation

In this step, a molecule reacts with a free radical to generate a new radical.



Chain termination

This step is also known as destruction of free radicals. This step involves a combination of two like or unlike radicals to form a new bond.



3.2 Addition Reactions

These reactions are characteristic of compounds containing multiple bonds. The alkene (=), alkynes (≡), C=O, C≡N react by addition to multiple bond. Thus in addition reaction there is increase in the number of groups attached to the substrate and decrease in its unsaturation.

Addition reactions are of four type namely electrophilic, nucleophilic, free radical and concerted. The first three are the two-step processes, with initial attack by electrophile, nucleophile or a free

radical. The second step consists of a combination of the resulting intermediate with a negative species, a positive species or a neutral entity. In addition, attack at the two carbon atoms of the double or triple bond is simultaneous.

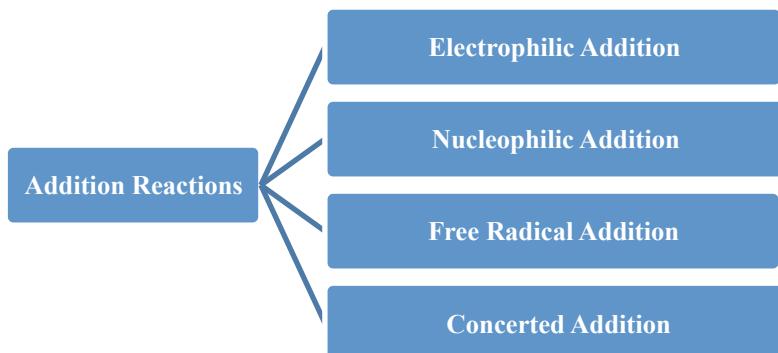
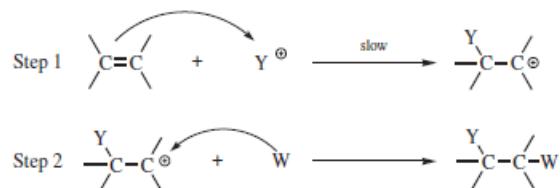


Fig 3: Types of addition reactions

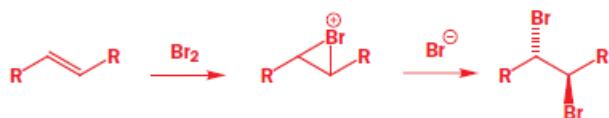
3.2.1 Electrophilic Addition Reactions

The first step is addition of electrophile by formation of σ bond through donation of π electrons to the electrophile and carbocation is formed. The next step is reaction of the positively charged intermediate (carbocation) with a species carrying lone pair or negative charge i.e nucleophiles. This step is the same as the second step of the S_N1 mechanism.

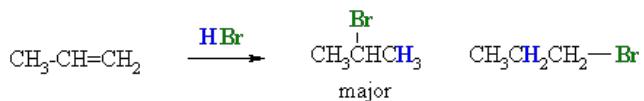


Examples of electrophilic addition reactions:

(a) Addition of bromine to alkenes: The addition reaction of bromine to alkenes proceeds via a cyclic bromonium ion intermediate. This intermediate is similar to those encountered in the neighbouring-group mechanism of nucleophilic substitution. This reaction is used as a colour test to detect the presence of multiple bonds. The brown colour of bromine disappears when it is added to a compound with double or triple bonds.

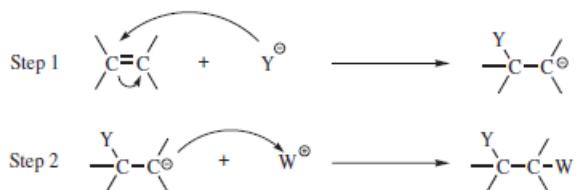


(b) Addition of unsymmetrical reagents to unsymmetrical alkenes (Markownikoff rule): For example in the reaction of propene with HBr, H^+ acts as an electrophile which is added to the carbon bearing double bond followed by attack of bromide ion (Br^-).



3.2.2 Nucleophilic Addition Reactions

Such reactions are encountered in compounds containing polar functional groups (C=O , $\text{C}\equiv\text{N}$, C=S). In the first step a nucleophile with its pair of electrons attacks the carbon atom of a double or triple bond, forming a carbanion. It is followed by a second step in which this carbanion reacts with a positive species.



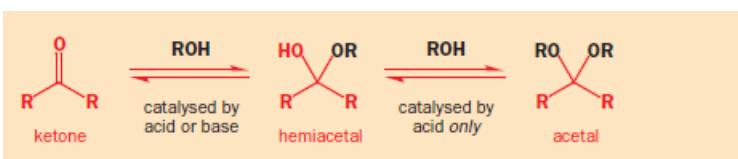
When the olefin contains a good leaving group (as defined for nucleophilic substitution), substitution is a side reaction. (i.e. a nucleophilic substitution at a vinylic substrate).

Examples of nucleophilic addition reactions:

(a) Addition of HCN to carbonyl group: In this reaction cyanide ion (CN^-) acts as a nucleophile which attacks the carbon of carbonyl group, the carbon-oxygen double bond breaks followed by capture of proton and a cyanohydrin is formed.



(b) Addition of alcohol to carbonyl compounds: Aldehydes or ketone react with one mole of alcohol to form hemiacetal or hemiketal, respectively. Reaction with second mole of alcohol gives acetal or ketal. In this reaction the alcohol with lone pair of electrons of oxygen atom acts as a nucleophile



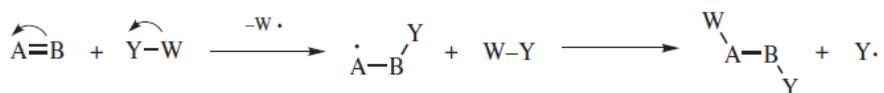
(c) Nucleophilic addition to carbon-carbon double bond (Michael reaction): In Michael reaction a nucleophile adds on to the β -carbon of an α,β -unsaturated system having electron withdrawing group. HY added to substrate having groups such as CHO, COR, COOR, CONH₂, CN, NO₂, SOR, SOOR etc. always give a product with Y⁻ bonding with the carbon away from the Z group and follows nucleophilic mechanism.



This 1,4- addition is called as cyanoethylation because Y is cyanoethylated.

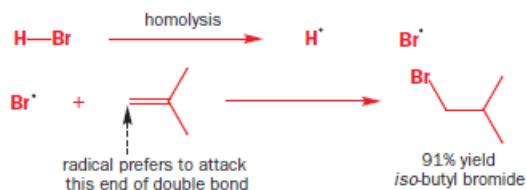
3.2.3 Free Radical Addition Reactions

Free radicals add to an unsaturated molecule to give a new radical intermediate which further reacts to give final product. The radical is generated by photolight or spontaneous dissociation.



Example of free radical addition reaction:

Addition of HBr to alkene in presence of peroxide (Anti-Markownikoff addition) is a type of free radical addition reaction. The peroxide acts as radical initiator. This is a stereoselective free-radical addition reaction.



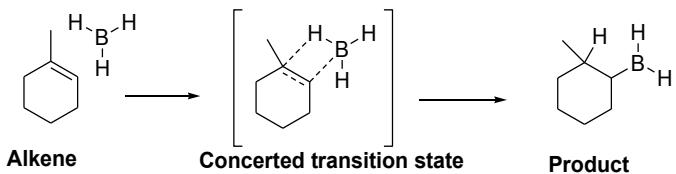
3.2.4. Concerted Addition Reactions

Concerted addition reactions occur by simultaneous attack at both the carbons. The initial attack is not at one carbon of the double bond, but both carbons are attacked simultaneously. Most of these reactions involve four-membered transition state but in few cases, there is a five- or six-membered transition state. In these cases, the addition to the double or triple bond must be *syn*. The most important reaction of this type is Diels-Alder reaction.



Example of concerted addition reaction:

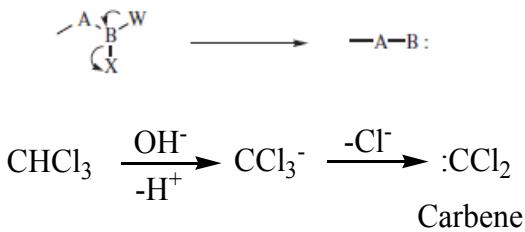
Hydroboration of alkene is a concerted addition reaction. Here, the formation of C-H and C-B bonds takes place at the same time of breaking of the B-H bond.



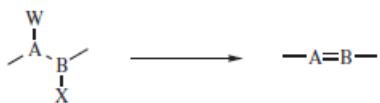
3.3 Elimination Reactions

In these reactions two atoms or groups attached to the carbon atom/s of the substrate molecule are eliminated. These are of three types α , β and γ eliminations.

α -elimination (or 1,1- elimination): The two groups are eliminated from same carbon, for example formation of carbene or nitrene.



β -elimination (or 1,2-elimination): This is the most common elimination reaction in which the two groups are eliminated from adjacent carbons creating a multiple bond. In most β -eliminations, the new bonds are $\text{C}=\text{C}$ or $\text{C}\equiv\text{C}$. The β -eliminations include acid catalysed dehydration of alcohols, Hofmann elimination, dehydrohalogenation.





γ -elimination: A three membered ring is formed in this case.

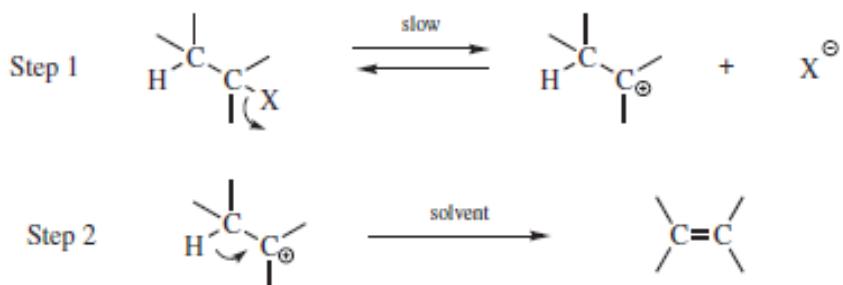


R = H or C_6H_5
X = F or OTs

The β -elimination reactions follow two pathways E1 and E2.

3.3.1 Unimolecular Elimination Mechanism (E1)

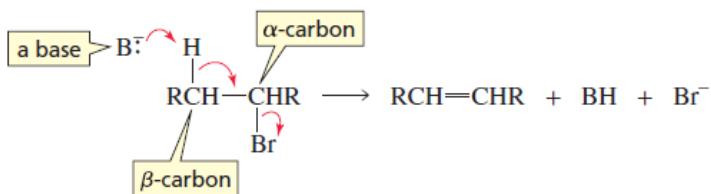
The E1 reaction needs no good base or nucleophile, it proceeds via formation of a carbocation. It is a two-step reaction involving formation of a carbocation followed by loss of proton giving more substituted alkene as major product. Here, formation of carbocation by ionization of substrate is the rate determining step. The carbocation so formed rapidly loses a β proton to a base, usually the solvent. E1 is analogous to $\text{S}_{\text{N}}1$ mechanism. The second step differs in that the solvent pulls a proton from the β carbon of a carbocation rather than attacking it at the positively charged carbon, as in the $\text{S}_{\text{N}}1$ process. In E1 reaction, the product should be completely non-stereospecific, since the carbocation is free to adopt its most stable conformation before losing proton.



3.3.2 Bimolecular Elimination Mechanism (E2)

In E2 mechanism a strong base abstracts proton from the substrate and the electron pair form π -bond with departure of leaving group, all this occurs in one step. The two groups are eliminated simultaneously. It occurs in one step thus follows second order kinetics i.e. first order in substrate and first order in base. E2 is analogous to the $\text{S}_{\text{N}}2$ mechanism and often competes with it.

Dehydrohalogenation of alkyl halides to alkene is a bimolecular elimination reaction.



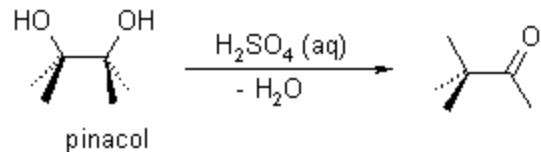
3.4. Rearrangement Reactions

Molecular rearrangements involve migration of an atom or a group from one atom to another in the same molecule. The rearrangement reactions proceed via the formation of cation, anion or radical. The 1,2-rearrangement, pericyclic reactions and metathesis occur via rearrangement. The atom A is called Migration Origin and B is the Migration terminus. The migration of any substituent from one atom to the atom adjacent to it is known as 1,2-shifts, but some are over longer distances.



Examples of rearrangement reactions:

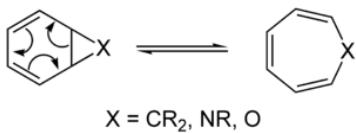
(a) Pinacol-Pinacolone rearrangement: Conversion of 2,3-dimethylbutan-2,3-diol into 2,2-dimethylbutan-3-one.



(b) Beckmann rearrangement: Conversion of an oxime to amide is a rearrangement reaction. In most Beckmann rearrangements, only the groups trans (usually called anti) to the hydroxyl group migrates.



(c) Pericyclic Reactions: A pericyclic reaction involves concerted bond reorganisation and the essential bonding changes within a cyclic array of the participating atomic centres. In these types of reaction neither ions nor radicals are formed as intermediate and remain unaffected by polar reagents. They take place either photochemically or thermally.



3.5 Oxidation and Reduction Reactions

Organic reactions are classified as oxidation or reduction depending on whether the substrate is oxidised or reduced. For this the functional groups are arranged in order of increasing oxidation state as follows:

Oxidation state -4 (alkane)

Oxidation state -2 (alkene, alcohol, alkyl halide, amine)

Oxidation state 0 (alkyne, carbonyl, dihalides, diols)

Oxidation state +2 (carboxylic acid, amide, trihalide)

Oxidation state +4 (carbon dioxide, carbon tetrachloride)

Oxidation is the conversion of a functional group in a molecule from one category to a higher one and reduction is the opposite. In oxidation gain of oxygen or/and loss of hydrogen takes place.

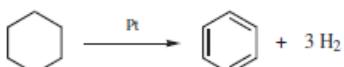
Reduction is opposite to that of oxidation as here loss of oxygen or gain of hydrogen takes place. Also there is no oxidation without a concurrent reduction.

Oxidation reactions are classified depending on the type of bond change involved.

Examples of oxidation reactions:

Elimination of hydrogen.

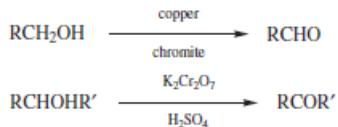
(a) Aromatisation: Conversion of cyclohexane to benzene in the presence of a catalyst is a type of oxidation reaction which proceeds via loss of hydrogen. The most frequently used reagents to affect aromatization are hydrogenation catalysts such as Pt, Pd, Ni etc. quinines, elements S, Se etc.



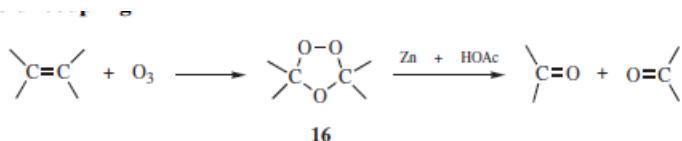
(b) Oxidation or dehydrogenation of alcohols to aldehydes and ketones. Conversion of alcohol to carbonyl: A variety of reagents such as CrO₃, pyridinium chlorochromate (PCC), pyridinium dichromate (PDC), DMSO/oxalyl chloride, DMSO/DCC, copper chromite, are used for oxidation of alcohols to aldehyde or ketone. Primary alcohols are converted to aldehydes and secondary alcohols are converted to ketones in four main ways:

- 1). With strong oxidizing agents .

- 2). By catalytic dehydrogenation.
- 3). With NBS and other chemoselective oxidising agents.



(c) Cleavage of carbon- carbon bonds *i.e.* Ozonolysis: Reaction of alkenes with ozone under suitable conditions leads to fission of carbon-carbon double bond via formation of an intermediate ozonide.

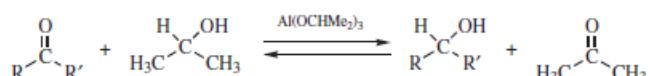


Examples of reduction reaction:

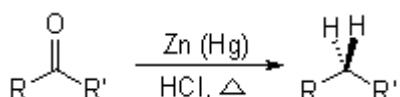
(a) Conversion of carbonyl to alcohol: When aldehydes or ketones are converted to alcohol the hydrogen content is increased thus it is a reduction reaction. The transfer of hydride ion by lithium hydride to carbonyl is such an example. There are two methods known for the conversion of carbonyl to alcohol, these are Clemmensen reduction and the Wolff kishner reduction.



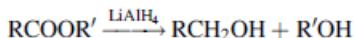
(b) Meerwein–Ponndorf–Verley reduction: It occurs in the presence of isopropyl alcohol and aluminum isopropoxide. The reaction is reversible in nature and the reaction reverse to it is named as the Oppenauer oxidation.



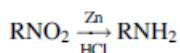
(c) Clemensen Reduction: In the Clemensen reduction a carbonyl compound is reduced to alkane using amalgamated zinc and hydrochloric acid. Ketones are reduced more often than aldehydes.



(d) Conversion of carboxylic ester to alcohol: Lithium hydride often brings out reduction of carboxylic ester by hydride transfer via formation of aldehyde in first step and further hydride transfer to the aldehyde leads to formation of alcohol. This reaction is of wide scope and has been used to reduce many esters. Other common reagents used are DIBAL, Lithium triethylborohydride, $\text{BH}_3\text{-SMe}_2$ in refluxing THF. NaBH_4 reduces phenolic esters especially those containing EWGs.



(e) Conversion of nitro compounds to amine: Conversion of nitro group to amine is a reduction reaction which involves loss of oxygen and gain of hydrogen.



Both aliphatic and aromatic nitro compounds can be reduced to amines, though the reaction has been applied much more often to aromatic nitro compounds. The other common reagents are Zn, Sn or/and acid, $\text{AlH}_3\text{-AlCl}_3$, TiCl_3 , $\text{Al-NiCl}_2\text{-THF}$, formic acid and Pd-C, etc.

4. Summary

- Organic reactions are of various types.
- Organic reactions are classified as substitution, addition, elimination, rearrangement, oxidation and reduction.
- These reactions differ mechanistically from each other and on the nature of attacking reagents.