

UNIT 13

ALKYL HALIDES |

Structure

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13.1 INTRODUCTION

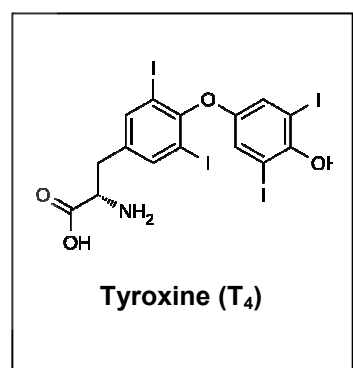
In earlier units of this Block, we have described the preparations and reactions of aromatic hydrocarbons. In this unit and in the next units, we will study halogen derivatives of hydrocarbons. Replacement of one or more hydrogen atoms in a hydrocarbon by halogen atom(s) [F, Cl, Br, or I] gives the halogen derivatives. These compounds are important laboratory and industrial solvents and serve as intermediates in the synthesis of other organic compounds. Many chlorohydrocarbons have acquired importance as insecticides. Although there are not many naturally occurring halogen derivatives, yet you might be familiar with one such compound, thyroxine (T_4)-a thyroid hormone.

In this unit, we shall take up the chemistry of the alkyl halides in detail. We shall begin with classification of halogen derivatives and go over to methods of the preparation of alkyl halides. We shall also discuss the reactivity of these halogen compounds and our main focus will be, on some important reactions such as nucleophilic substitution (S_N) and elimination (E) reactions. Finally, we shall take up uses of halogen derivatives and the methods for their detection.

Expected Learning Outcomes

After studying this unit, you should be able to:

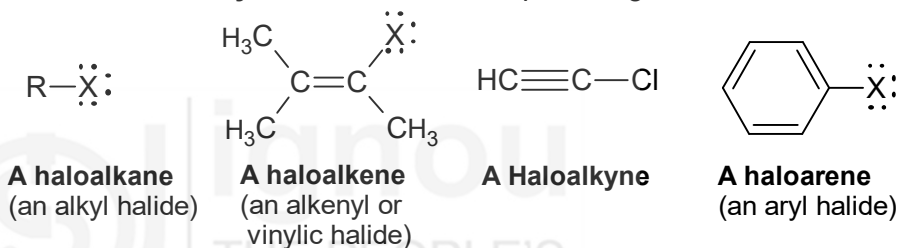
- ❖ classify the halogen derivatives;



- ❖ outline the methods of preparation of alkyl halides;
- ❖ list the physical properties of halogen derivatives;
- ❖ describe the reactions of alkyl halides, specially nucleophilic substitution and elimination reactions in detail;
- ❖ list and describe the industrial uses of halogen derivatives; and
- ❖ describe the laboratory detection of halogen derivatives.

13.2 CLASSIFICATION OF HALOGEN DERIVATIVES

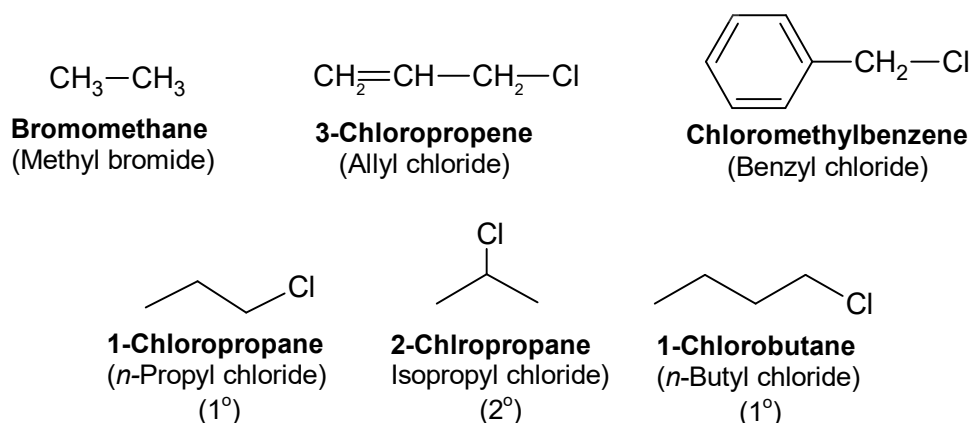
The halogen derivatives are conveniently divided into three classes depending upon the nature of the hydrocarbon residue to which the halogen atom is attached: (i) Alkyl halides (haloalkanes) (ii) Alkenyl halides (haloalkenes) (iii) Aryl halides (haloarenes). Compounds in which the halogen atom is bonded to an alkyl or a substituted alkyl-group are called **alkyl halides**. Compounds in which a halogen atom is attached to a carbon atom which is attached to another carbon atom by a double bond are called **alkenyl** (vinylic or vinyl) **halides**. Finally, compounds in which one of the hydrogen of an aromatic ring is replaced by a halogen atom are called **aryl halides**. A few examples are given below:

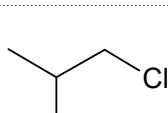


In polyfunctional compounds, where groups other than halogen functional groups are present, one group is identified as the principal functional group and this principal functional group is used as a suffix in the name of the compound. The priorities for selection of principal functional group are given below in the order of decreasing precedence: carboxylic acid, sulphonic acid, ester, acid anhydride, acylhalide, amide, nitrile, aldehyde, ketone, alcohol, thiol, amine, imine, alkyne, alkene, ethers, halides, nitro. Notice the IUPAC name of allyl chloride in main text.

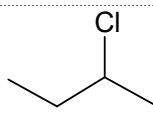
Before going further in details of classification of alkyl halides, just to recall, in IUPAC system of nomenclature, a halo- (i.e. fluoro-, chloro-, bromo-, or iodo-) is prefixed and the carbon chain is so numbered so as to give the lowest number to the carbon to which the halogen is attached. When more than one of halogen atoms are present, their names are arranged in alphabetical order. Common names are arrived at by writing the name of alkyl group followed by the name of the halide.

Alkyl halides are further classified on the basis of nature of carbon atom [i.e. primary (1°), $\text{RCH}_2\text{-X}$; secondary (2°), $\text{R}_2\text{CH-X}$ or tertiary (3°), $\text{R}_3\text{C-X}$] and on the basis of number of halogen atoms present in a molecule [i.e. mono-, di-, tri- or tetra-]. Now we will consider few examples of simple alkyl halides from each class (name given in brackets are common names):

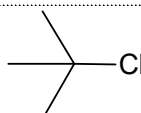




1-Chloro-2-methylpropane
(Isobutyl chloride)
(1°)

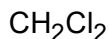


2-Chlorobutane
(sec-Butyl chloride)
(2°)



2-chloro-2-methylpropane
(*tert*-Butyl chloride)
(3°)

Di-, tri-, and tetrachloromethanes are examples of di-, tri-, and tetra halogen derivatives, respectively,



Dichloromethane
(Methylene chloride)



Trichloromethane
(Chloroform)

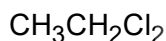


Tetrachloromethane
(Carbon tetrachloride)

These halogen derivatives are excellent solvents for nonpolar and slightly polar substances.

The dihalogen derivatives of alkyl halides can be subdivided into two types:

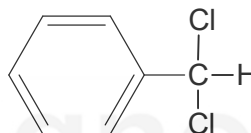
- i) **Geminaldihalides:** In these both halogen atoms are attached to the same carbon atom i.e., they are in geminal (gem-) position. Geminaldihalides are also referred to as alkylidene halides.



1,1-Dichloroethane
(Ethylidene chloride)



2,2-Dibromopropane
(Isopropylidenedibromide)



Dichloromethylbenzene
(Benzylidene chloride or benzal chloride)

- ii) **Vicinal dihalides:** When two halogen atoms are attached to adjacent carbon atoms, they are said to be in **vicinal (vic-)** position and such compounds are also named as the dihalides of the alkene from which they may be prepared by addition of the halogen, e.g.



1, 2-Dibromoethane
(Ethylene dibromide)

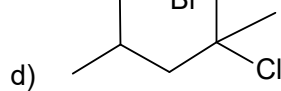
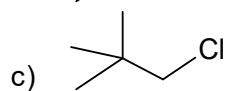
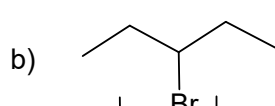
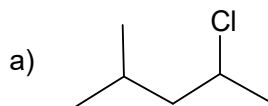


2-Dichloropropane
(Propylene dichloride)

We have discussed above classification of halogen derivatives. In the next section, we shall be discussing the preparations of mono halogen derivatives of alkyl halides and alkenyl halides. We will take up aryl halides separately in next unit. Before that, try the following SAQ to test your understanding of the classification of halogen derivatives.

SAQ 1

Classify each of the following alkyl halides as 1°, 2°, or 3°. Also write IUPAC name of each compound.

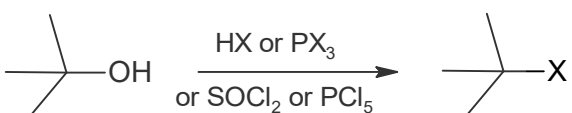
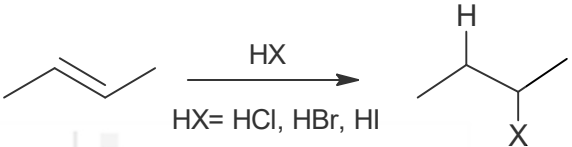
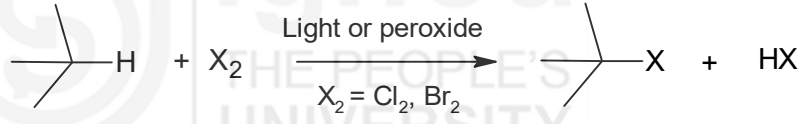
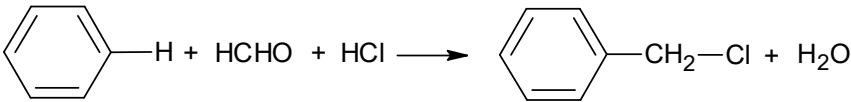


13.3 PREPARATION OF ALKYL HALIDES

We have already looked at several methods of preparation of halogen derivatives in earlier units of 1st semester course. In this section, we shall briefly review these methods and also take up some other methods for the preparation of halogen derivatives.

Alkyl halides can be prepared from alcohols, alkenes, alkanes, Grignard reagents, carboxylic acids, other halides and by chloromethylation of benzene. General reactions of these methods of preparation are summarised below in Table 13.1.

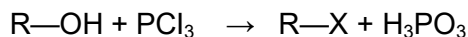
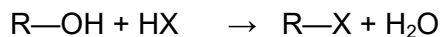
Table 13.1: Preparation of alkyl halides

From Alcohols	
From Alkenes	
From Alkanes	
From Grignard Reagents	$\text{RMgX} + \text{X}_2 \longrightarrow \text{CH}_3\text{-X} + \text{MgX}_2$ <p style="text-align: center;">$\text{X}_2 = \text{Cl}_2, \text{Br}_2$</p>
From Carboxylic Acids	$\text{RCOOAg} + \text{Br}_2 \longrightarrow \text{R-Br} + \text{AgBr} + \text{CO}_2$
From Halide Exchange	$\text{R-X} + \text{KI} \longrightarrow \text{R-I} + \text{KX}$
From Chloromethylation of Benzene	

Let us study these methods of preparation in a brief manner.

- i) **From alcohols:** The most widely used method for the preparation of alkyl halides is from alcohols. The hydroxyl group of the alcohol (R—OH) can be replaced by a halogen atom by using either a hydrogen halide (HX), a phosphorus halide (PX₃ or PCl₅), or thionyl chloride (SOCl₂). These reactions

will be discussed in more detail in the next unit. The net reaction is represented by the equations,

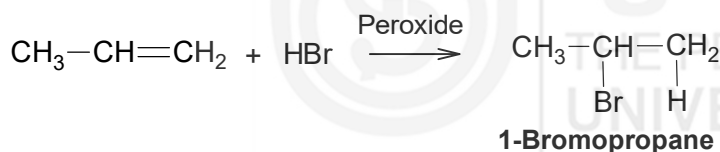
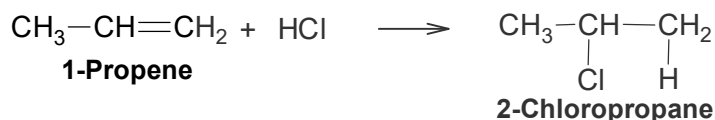


Phenylmethanol
(Benzyl alcohol)

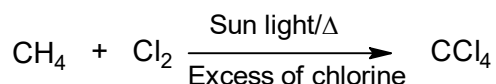
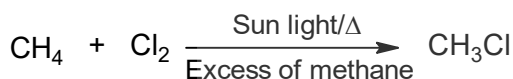
Chloromethylbenzene
(Benzyl chloride)

- ii) **From alkenes:** Hydrogen halides (HCl, HBr, HI) reacts with alkenes to form alkyl halides. The mode of addition follows Markownikoff's rule except for the addition of hydrogen bromide in the presence of peroxide. The mechanisms for both modes of additions were shown in Unit 17 of first semester course.

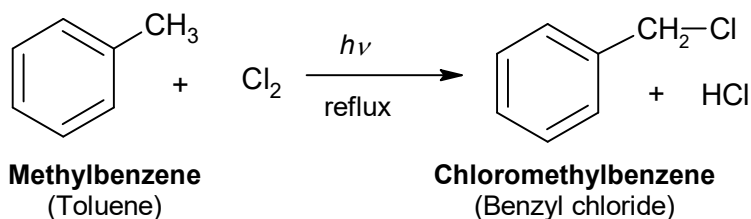
Examples:



- iii) **From Alkanes:** Direct halogenation of alkanes is of limited application because in most cases mixture of mono and polyhalogenated compounds is formed. You have learned in Unit 17 that chloromethane, however, can be prepared directly by photochlorination or heating if a large excess of methane is employed. Similarly tetrachloromethane (carbontetrachloride), CCl_4 , can also be prepared from methane if a large excess of chlorine is used.

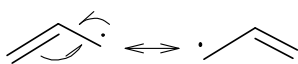


Chloromethylbenzene can also be similarly prepared.

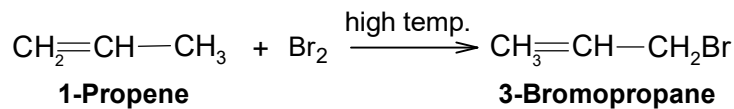


Allylic carbon: A carbon adjacent to a carbon-carbon double bond.

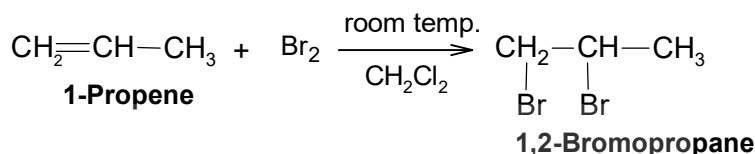
Selectivity in allylic substitution is due to the resonance stability of intermediate allylic radical.



The above mentioned reactions are examples of free radical substitution reactions. Alkenes having allylic carbon undergo similar type of reactions at high temperature or in the presence of light rather than usual electrophilic addition reactions. Such reactions are called allylic substitution.



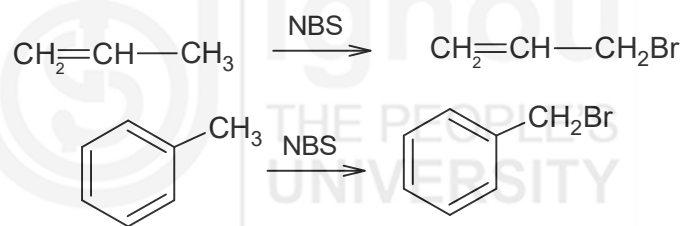
Allylic substitution



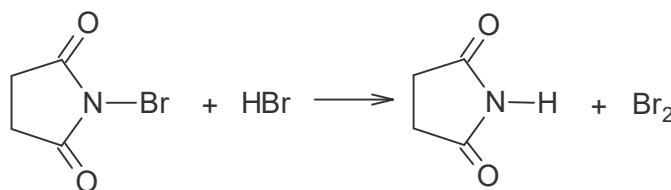
Electrophilic addition

This is because in the first reaction above, the formation of π -complex which is an intermediate in halogen addition reaction, is unfavourable in the absence of polar solvent. Therefore, substitution is favoured over addition. At high temperature concentration of halogen radicals is much higher than at room temperature, which further accelerates substitution.

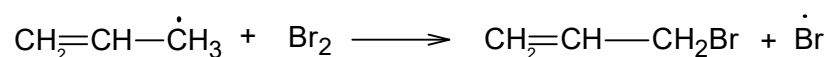
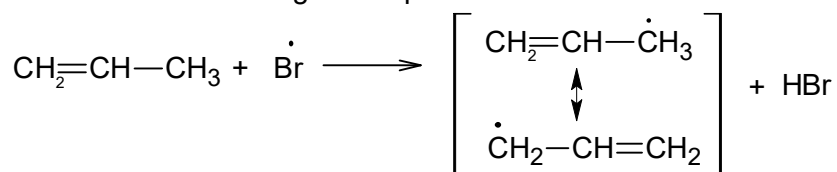
N-Bromosuccinimide (NBS) deserves a special mention because it is a specific reagent for bromination at allylic and benzylic positions in alkenes.



A mechanism has been proposed for such reactions, in which NBS acts as a bromine reservoir maintaining a low concentration of molecular bromine by reacting with HBr, which is initially formed in a side reaction:

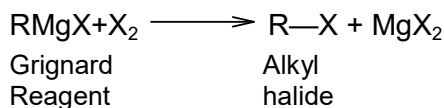


Bromine molecule dissociates into bromine atoms on heating or on exposure to light. Radical bromine abstracts hydrogen from the allylic position and generates a resonance-stabilised allylic radical which then reacts with molecular bromine to give the product.



The chain then continues with the production of HBr and bromine atoms. A low concentration of bromine favours allylic bromination over addition to the double bond.

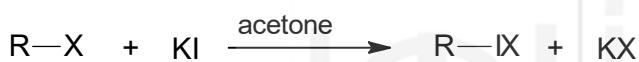
- iv) **From Grignard reagents:** Direct reaction of alkyl or aryl halides with metallic magnesium in a dry solvent (ether) gives the Grignard reagent, a valuable intermediate in synthetic organic chemistry. Grignard reagents react with halogens to give alkyl halides.



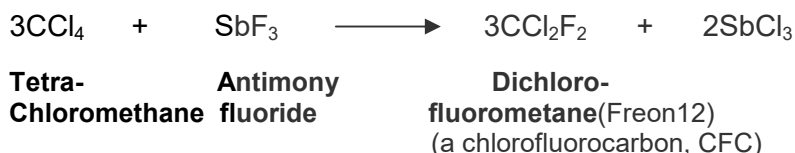
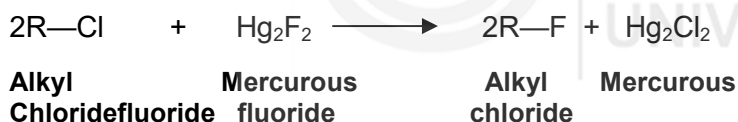
- v) **From carboxylic acids:** The dry silver salt of a carboxylic acid upon refluxing with bromine in tetrachloromethane (carbon tetrachloride) affords the corresponding alkyl bromide. This reaction is known as **Hunsdiecker reaction**.



- vi) **From Halide exchange:** This is a good procedure for preparing alkyl iodides and alkyl fluorides.

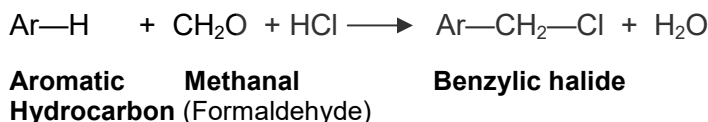


Alkyl fluorides often are prepared by the reaction of metallic fluoride such as AgF, Hg₂F₂, CoF₂ or SbF₃. The reaction is termed as **Swarts reaction**.



Chlorofluorocarbons (CFC) also called Freons are inert nontoxic gases used as refrigerants in air-conditioners and refrigerators. Freon 12 is the most commonly used refrigerant. Unfortunately Freons catalyse the decomposition of ozone and thus can destroy the protective layer that surrounds the earth. For this reason most of countries in the world have banned the use of Freons.

- vii) **From Chloromethylation of benzene:** This method is used to prepare benzylic halides.



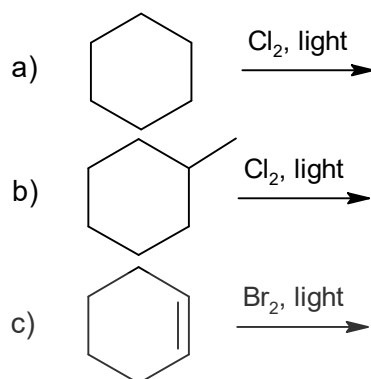
SAQ 2

Write equations showing the preparation of the following halides from the starting materials indicated.

- a) C₆H₅CHBrCH₃ from C₆H₅CH₂CH₃ c) 1-bromopropane from propene
 b) CH₃CHBrCH₃ from CH₃CHOHCH₃ d) 1,2-dibromopropane from propene

SAQ 3

Predict the monohalogenation product that might be formed in the following reactions.



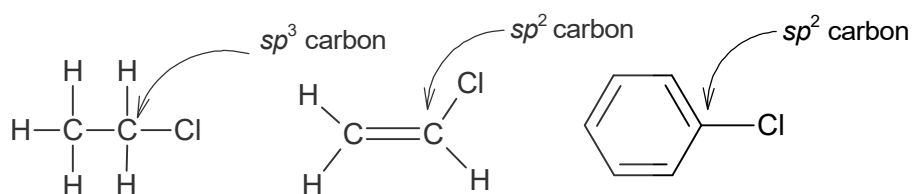
13.4 STRUCTURE AND PROPERTIES OF HALOGEN DERIVATIVES

In the previous section, we have discussed the preparation of alkyl halides. Now we will discuss to the structure and physical properties of halogen derivatives along with chemical properties of alkyl halides.

13.4.1 Structure of Halogen Derivatives

In a halogen derivative, halogen atom is the functional group, and the C–X bond is the site of chemical reactivity. As might be expected, the nature of the chemical bond between the halogen and carbon decides the reactivity of halogen derivatives.

In the alkyl halide, the carbon-halogen sigma bond results through overlap of the sp^3 hybrid orbital with the p orbital of the halogen atom. The carbon halogen sigma bond in alkenyl and aryl halides results from the overlap of sp^2 hybrid orbital of the carbon with a halogen p orbital.



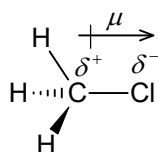
Electronegativity on the Pauling and Sanderson scales

Element	Pauling	Sanderson
F	4.0	4.000
Cl	3.0	3.475
Br	2.8	3.219
I	2.5	2.778
C	2.5	2.746

As you know, the bond formed by halogen with sp^2 hybridised carbon is shorter and stronger than the bond formed with a sp^3 hybridised carbon because of the higher s character. This difference in the nature of the C–X bond is mainly responsible for different behaviour of aryl and alkenyl halides as compared to alkyl halides. To further explain the unique chemistry of aryl and alkenyl halides, we shall study the reactions of chlorobenzene and chloroethene in next unit. Let us first examine the nature of the C–X bond in alkyl halides.

You may recall that halogens are more electronegative than carbon and thus the C–X bond of alkyl halide is polarised and the electron density along the C–X bond increases in the direction of X. This effect places a partial negative charge (δ^-) on the halogen atom and a partial positive charge (δ^+) on the carbon atom. The

resulting dipole moment is appreciable and governs a substantial part of the chemical and physical properties of the halogen derivatives.



The magnitude of dipole moment depends on the electronegativities of the bonded atoms. For methyl halides, dipole moment is summarised in Table 13.2.

Table 13.2 : Dipole Moments of Methyl Halides

Compound	Dipole moment μ , D (C m)
CH ₃ F	6.16×10^{-30} (1.85 D*)
CH ₃ Cl	6.23×10^{-30} (1.87 D)
CH ₃ Br	6.03×10^{-30} (1.81 D)
CH ₃ I	5.40×10^{-30} (1.62 D)

The dipole moment (μ) is a measure of the polarity of the molecule. It is the product of charge (e) and distance (d).

$$\mu = e \times d$$

*Where D is debye unit, $1 \text{ D} = 3.33 \times 10^{-30} \text{ C m}$ (Coulomb/meter)

Another important factor on which the nature of C–X bond depends is its bond strength. Bond enthalpies, which measure the bond strength, decrease as we go down the group in the periodic table. This is because, the size of halogen atom increases as we go down the group in the periodic table, fluorine atom is the smallest and iodine atom, the largest. Consequently the carbon-halogen bond length also increases from C–F to C–I and bond strength decreases from C–F to C–I. Bond lengths and bond enthalpies of typical halides are given in Table 13.3. These bond energy values show that C–I bond is the weakest bond and C–F bond is the strongest bond. Therefore, the order of reactivity of haloalkanes is iodoalkane > bromoalkane > chloroalkane > fluoroalkane. We will further go in details of the relative reactivity of alkyl halides in subsequent sections. We will also explain how the slight positive charge on the carbon attached to halogen atom is mainly responsible for the nucleophilic substitution (S_N) reactions of halogen derivatives.

Table 13.3: Carbon-Halogen (C–X) Bond Length and Bond Enthalpies

Bond	Bond length/pm	C–X Bond enthalpy/ kJ mol^{-1}
C–F	139	452
C–Cl	178	351
C–Br	193	293
C–I	214	234

Thus we can summarise that **both dipole moment and bond strength of C–X govern a substantial part of the chemical and physical properties of the halogen derivatives.**

13.4.2 Physical Properties of Halogen Derivatives

The alkyl halide has a higher boiling point than an alkane of comparable size and shape. For example, the boiling points of ethane and bromomethane are 184 K and 277.5 K, respectively. Although both the molecules are approximately of same size. The boiling point of bromomethane is considerably higher. This difference in boiling point is due to the dipole moment in bromomethane. The dipole-dipole interactions increase van der Waals forces among molecules; therefore, more energy is needed to overcome these forces before boiling. The physical properties such as boiling points and densities of some alkyl halides, aryl halides and alkenyl halides are summarised in Table 13.3. Common names of some of them are also given.

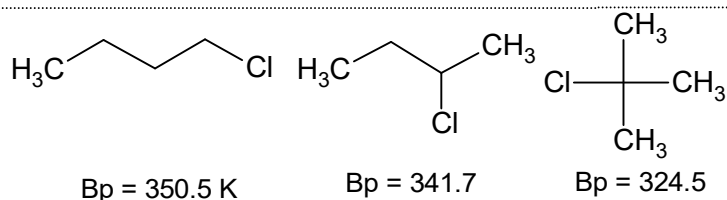
Van der Waals forces: A group of intermolecular attractive forces including dipole-dipole, dipole-induced dipole, and induced dipole-induced dipole forces. These forces are very weak in comparison to electrostatic ionic forces in ionic compounds.

Table 13.3: Physical properties of halogen derivatives

IUPAC Name	Common Name	Formula	Bp, K	Density, kg dm^{-3} at 293 K
Alkyl halides				
Fluoromethane	Methylfluoride	CH_3F	195	Gas
Chloromethane	Methylchloride	CH_3Cl	249	Gas
Bromomethane	Methylbromide	CH_3Br	277.5	Gas
Iodomethane	Methyliodide	CH_3I	315.8	2.28
Dichloromethane	Methylene chloride	CH_2Cl_2	313	1.34
Trichloromethane	Chloroform	CHCl_3	334	1.49
Tetrachloromethane	Carbontetrachloride	CCl_4	350	1.60
Aryl halides				
Fluorobenzene	—	$\text{C}_6\text{H}_5\text{F}$	358	1.024
Chlorobenzene	—	$\text{C}_6\text{H}_5\text{Cl}$	405	1.107
Bromobenzene	—	$\text{C}_6\text{H}_5\text{Br}$	429	1.495
Iodobenzene	—	$\text{C}_6\text{H}_5\text{I}$	462	1.832
Alkenyl halides				
Chloroethene	Vinyl chloride	$\text{CH}_2=\text{CHCl}$	259	Gas

Note the increase in boiling point and density with the increase in the atomic mass and atomic size of the halogens atom. The table emphasises also the increase in the boiling point with the progressive replacement of the hydrogen atoms with halogen atoms. These effects are related to the enhancement of van der Waal's attraction with the increase in molecular volume. Compare, for example, the boiling points of CH_3Cl , CH_2Cl_2 , CHCl_3 , and CCl_4 . The density would also increase in the same way.

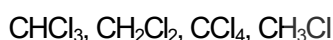
The boiling points of higher alkyl halides increase with the increase in mass and size. Boiling points of isomeric alkyl halides decrease with increase in branching. For example, 2-chloro-2-methylpropane has the lowest boiling point among the three isomers.



In general, halogen compounds are insoluble in water but are readily soluble in organic solvents and with the exception of some fluoro and mono-chloro compounds, they are more dense than water. Aryl halides are fairly pleasant smelling liquids, but benzylic halides having the structure ArCH_2X are irritating to the eyes, skin and nasal passage. The toxicity varies. However, the polychlorinated hydrocarbons such as CCl_4 and $\text{CHCl}_2\text{CHCl}_2$ are quite toxic and should be used with care.

SAQ 4

Arrange the following molecules in order of increasing boiling points. Give reason for this trend.



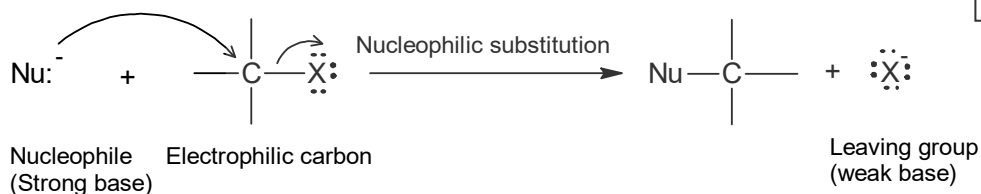
13.4.3 Chemical Properties of Alkyl Halides

Most important reactions of alkyl halides are **nucleophilic substitution (S_N)** and **elimination (E)**. In this section we shall take up a fairly detailed description of these reactions. We have already encountered the term nucleophilic reagent or nucleophile and have learned that it is applied to an electron rich atom or group such as,

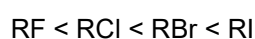


- 1) **Substitution reactions:** As explained earlier the C–X bond is polar bond, and the carbon to which halogen group is attached carries a positive charge because of the higher electronegativity of halogens compared to carbon. The carbon atom is, therefore, susceptible to attack by a nucleophile.

Nucleophilic substitution refers to a reaction in which an electron-rich nucleophile, Nu^- , replaces a leaving group, X^- .



If we regard the reaction as a type of Lewis acid-base reaction, then we can understand that it tends to occur because of the formation of the halide ion which, as the conjugate base of a strong acid (HX), would be a weak base. Accordingly, a weak base like the halide ion is said to be a good **leaving group**. The order of reactivity of the alkyl halides increases from fluoro-substituted to iodo-substituted compounds



The reason of this order is that the iodide ion, being the weakest base as the conjugate base of the strongest acid, HI, is the best leaving group, the fluoride ion being a stronger base is the poor leaving group.

Now let us summarise some nucleophilic substitution reactions of alkyl halides in Table 13.4.

Table 13.4: Some Nucleophilic Substitution Reactions

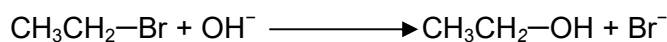
Reaction : $R-\ddot{X}: + Nu:^- \longrightarrow :\ddot{X}:^- + R-Nu$			
Nucleophile	Products	Class of compounds formed	
$:\ddot{O}H^-$ (Hydroxide)	\longrightarrow	$R-\ddot{O}H$	An alcohol
$H_2\ddot{O}:$ (Water)	\longrightarrow	$R-\overset{+}{\ddot{O}}H_2$	An alcohol (after loss of proton)
$:\ddot{O}R$ (Alkoxide)	\longrightarrow	$R-\ddot{O}R$	An ether
$:\ddot{S}H$ (Thiolate)	\longrightarrow	$R-\ddot{S}H$	A thiol
$:\ddot{S}R$ (Alkanethiolate)	\longrightarrow	$R-\ddot{S}R$	A sulphide
$:\bar{C}\equiv CH$ (Alkynyl anion)	\longrightarrow	$RC\equiv CH$	An alkyne
$:\bar{C}\equiv N:$ (Cyanide)	\longrightarrow	$RC\equiv N:$	A nitrile
$:\ddot{I}:$ (Iodide ion)	\longrightarrow	$R-\ddot{I}:$	An alkyl iodide
$:NH_3$ (Ammonia)	\longrightarrow	$R-NH_3^+$	An alkylammonium ion
$:NR'_3$ (Amine)	\longrightarrow	$R-NR'_3$	An alkylammonium ion
$:\bar{N}_3$ (Azide)	\longrightarrow	$R-N_3$	An alkyl azide

On the basis of the mechanism of substitution reactions, nucleophilic substitution reaction can be divided into two types:

- S_N2 reactions (S_N2 means 'substitution, nucleophilic bimolecular')
- S_N1 reactions (S_N1 means 'substitution, nucleophilic unimolecular')

The terms bimolecular and unimolecular are related to the number of molecules involved in the rate determining step in these reactions. Now, let us consider these reactions in detail.

The S_N2 reaction: The reaction of bromoethane with the hydroxide ion to yield ethanol and bromide ion is a typical example of S_N2 reaction.



Bromoethane

Ethanol

In general methyl or primary alkyl halides undergo S_N2 reaction with any relatively strong nucleophile: OH^- , OR^- , CN^- etc. Secondary alkyl halides can also undergo S_N2 reactions, but, tertiary alkyl halides do not. The above reaction has been found to follow second order kinetics which means that the rate of the reaction is proportional to the concentrations of both the alkyl halide and the hydroxide ion. Thus, for the above reaction,

$$\text{Rate} = k_2[C_2H_5Br][OH^-]$$

Where k_2 is the rate constant and $[C_2H_5Br]$ and $[OH^-]$ represent the concentrations in mole dm^{-3} of the alkyl halide and the hydroxide ion, respectively.

Mechanism: On the basis of reaction kinetics and the stereochemistry of S_N2 reactions, a one step, concerted mechanism is proposed.

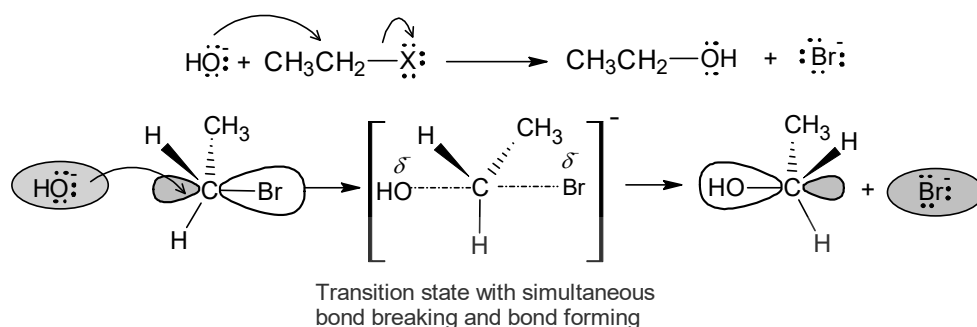


Fig. 13.1: The mechanism for S_N2 reaction. The dashed lines are depicting partially formed or broken bonds.

Note how the hydroxide ion attacks from the rear, away from the negatively charged field of the bromide ion. As the hydroxide ion begins to bond to the carbon atom from the rear, the bromine begins to leave as the bromide ion from the front. Groups larger than hydrogen tend to block the approach of the nucleophile, so methyl halides are more reactive than other primary halides. Table 13.5 shows the effect of the structure of alkyl halides over the reaction rate. In this table we have given average reaction rates (taking the reaction rate for ethyl halides are one) of S_N2 reaction of some alkyl halides.

In an S_N2 reaction, the other three bonds, (which are not taking part in substitution change) to the central carbon progressively flatten out and flip to the other side of the carbon in a manner similar to the spokes of an umbrella inverting in a windstorm. The flipping is called inversion of configuration, or Walden inversion, which you have already studied in Unit 3.

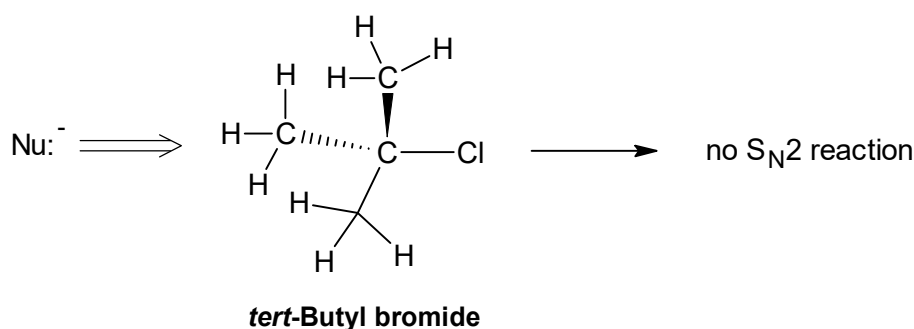
Table 13.5: Effect of branching in the alkyl halide on the rate of S_N2 reaction

Alkyl halide	Reaction rate
CH_3-X	30
CH_3CH_2-X	1
$(CH_3)_2CH-X$	0.02
$(CH_3)_3C-X$	0

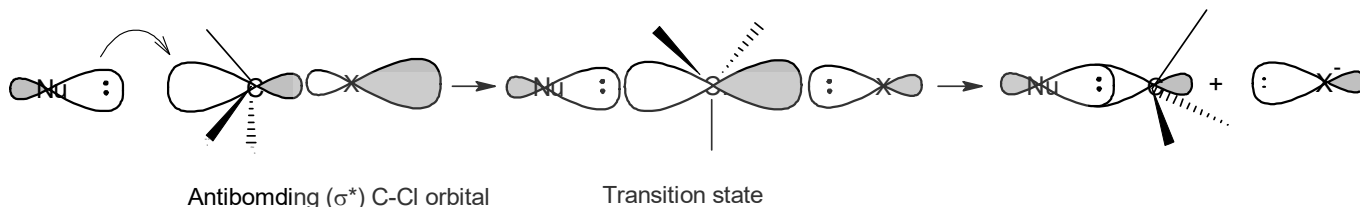
Therefore, among alkyl halides, order of relative rate is



This order of reactivity is interpreted to be due to steric hindrance, which means obstruction of space. The more the number of alkyl groups around the carbon holding the halogen, the more they hinder the nucleophile approaching at backside of that carbon.



Molecular orbital model provides a good description of the bonding interactions that occur in the S_N2 process. The filled nonbonding orbital of nucleophile is attacking from the backside of the antibonding molecular orbital, σ^* , of the C-X bond, weakening the C-X bond as the new C-Nu, σ bond becomes stronger. The back side interaction of nucleophile is the most effective way to fill this nonbonding, σ^* orbital, which result in breaking of the C-X bond. Thus both valence bond and molecular orbital models predict that the S_N2 reaction proceeds through a transition state with the inversion of the configuration.



In the transition state, the hybridisation of the central carbon atom changes from sp^3 to sp^2 . The geometry of the transition state is trigonal bipyramidal with one bond partially forming and one bond partially breaking. Finally, sp^3 hybridisation is reestablished in the product with inversion of configuration. The potential energy diagram of S_N2 reaction is given in Fig. 13.2, which illustrates potential energy change during the formation of substituted product.

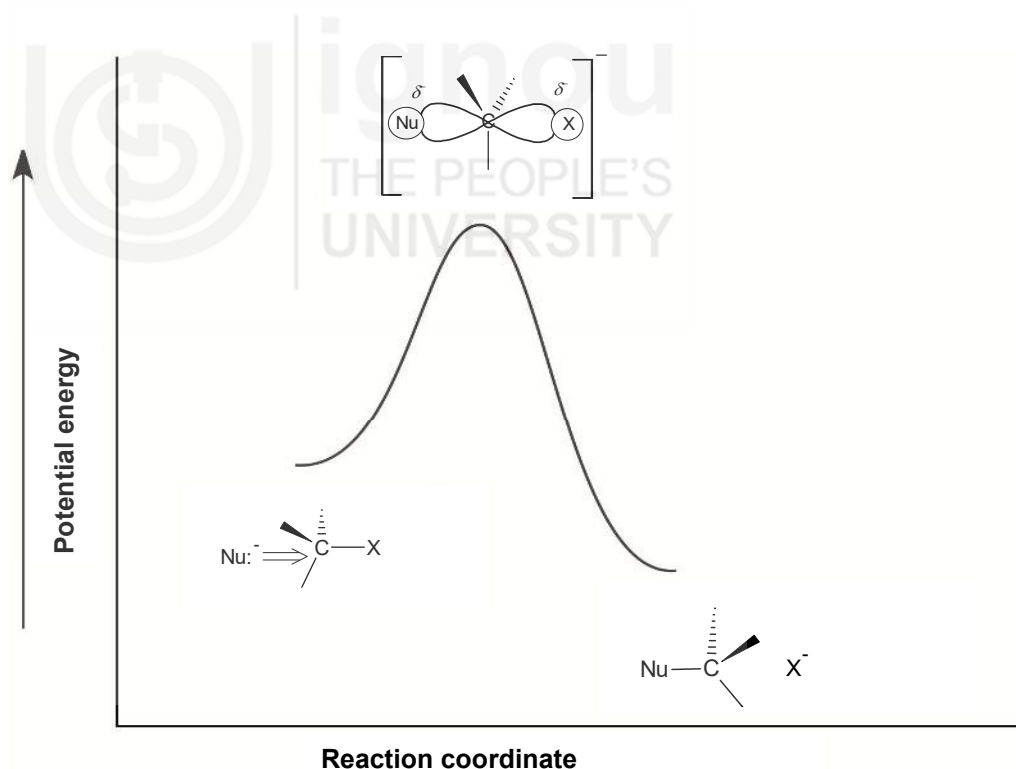


Fig. 13.2: Potential energy diagram for the S_N2 reaction. Higher energy state indicates transition state.

The S_N1 reaction:

You can see from Table 13.5, that the tertiary alkyl halides do not undergo S_N2 reaction. And yet when tertiary butyl bromide is treated even with a very weak base, (such as H_2O or CH_3CH_2OH) substitution takes place. Now, the question arises, if tertiary alkyl halides cannot undergo S_N2 reaction, how are the

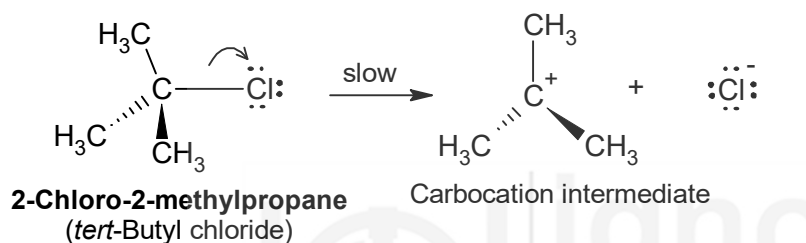
substitution products formed? The answer is that tertiary alkyl halides undergo substitution by a different mechanism, called the S_N1 reaction (substitution, nucleophilic, unimolecular). An example of such a reaction is the hydrolysis of 2-chloro-2-methylpropane with water. This reaction is found to be of first order (S_N1). That means the rate of the reaction is proportional to the concentration of the one reacting species i.e. alkyl halide and independent of the concentration of the nucleophile.

$$\text{Rate} = k_1 [(\text{CH}_3)_3\text{CCl}]$$

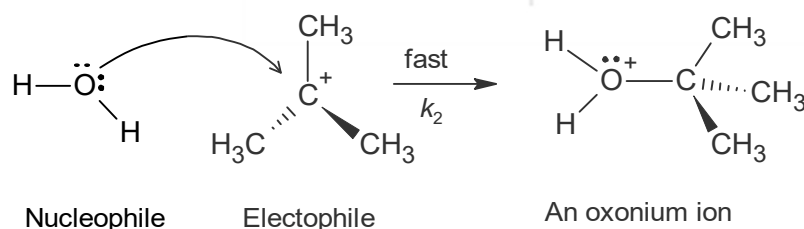
In this equation, k_1 represents the first order rate constant and $[(\text{CH}_3)_3\text{CCl}]$ represents the concentration of the alkyl halide in mole dm^{-3} .

Mechanism: On the basis of reaction kinetics and stereochemistry of S_N1 reaction, a two steps mechanism has been proposed for this reaction.

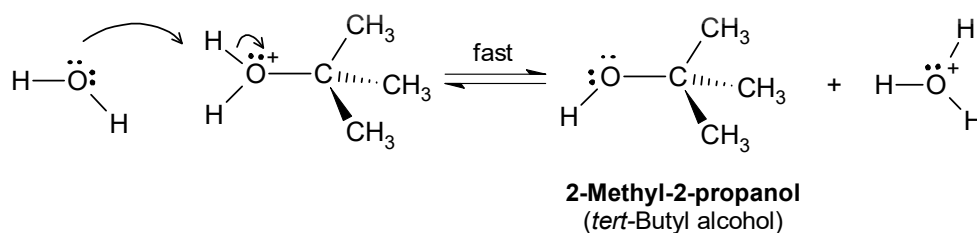
Step 1: Ionisation of the C–X bond forms a carbocation intermediate. This is the relatively slow, rate determining step.



Step 2: Carbocation (an electrophile) reacts with water (a nucleophile) to form an oxonium ion.



Proton transfer from the oxonium ion to water completes the reaction and gives 2-methyl-2-propanol (*tert*-butyl alcohol)

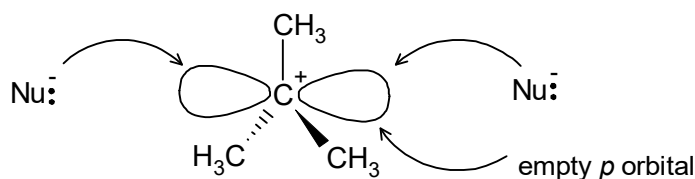


From the above mechanism it is clear that the first step in this mechanism is ionisation of the alkyl halide to a carbocation intermediate. This ionisation is a simple heterolytic bond cleavage. In the second step, a nucleophile may approach the central carbon atom from either side with equal probability

Nucleophiles such as H_2O or $\text{CH}_3\text{CH}_2\text{OH}$ are also used as the solvents. Substitution reactions of such nucleophiles are sometime called solvolysis reactions (from solvent and by "breaking down" or "loosing").

In most stepwise reactions, the slowest step in the entire sequence is the rate-determining step as a reaction cannot proceed faster than its slowest step does.

(unlike the S_N2 reaction where the nucleophile approaches only from the back). According to valence bond approach, the central carbon atom of carbocation is sp^2 hybridised and it has a trigonal planar geometry and, therefore, the nucleophile may engage the empty p orbital from either side of the molecule.



Thus, S_N1 reaction of an optically active alkyl halide should give racemic substitution products. The potential energy diagram of S_N1 reaction is given in Fig. 13.3. Step 1 has high energy of activation and is, therefore, the slow step. As shown in this figure, an intermediate carbocation has lower energy than transition states shown as I and II where bond breaking and bond making actually occur.

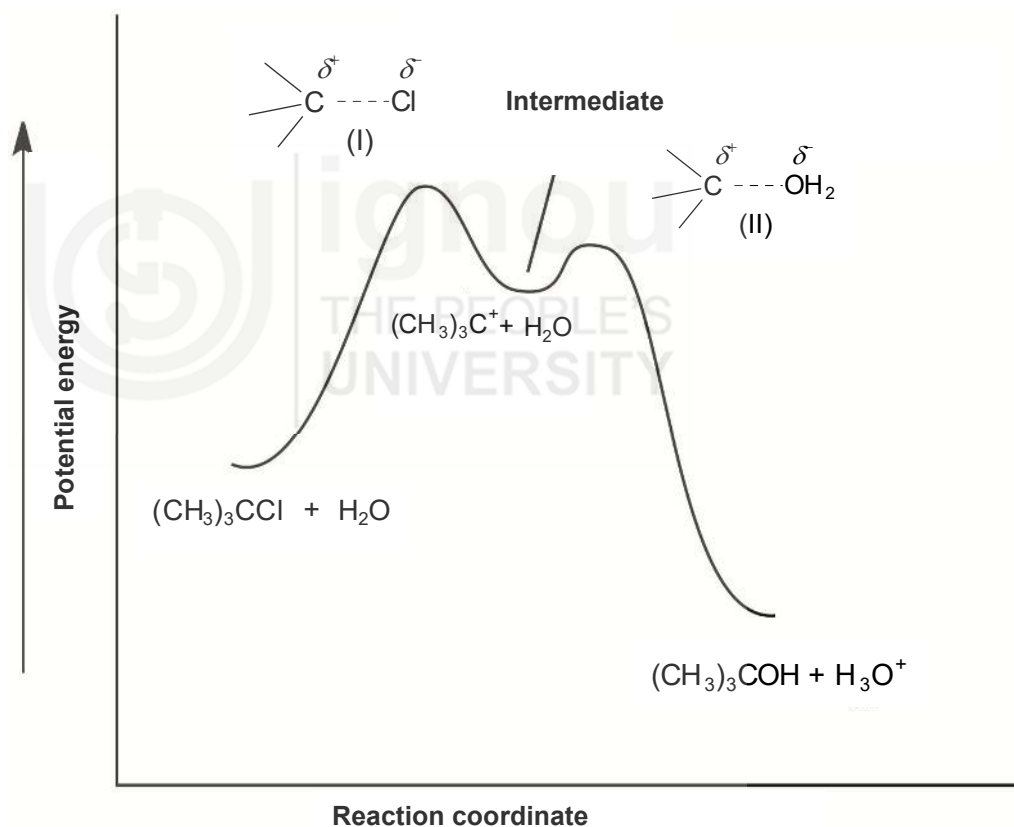


Fig. 13.3: Potential energy diagram for hydrolysis of 2-chloro-2-methylpropane by S_N1 mechanism. You can see two transition states. The first (I) is for formation of the carbocation intermediate, the second (II) is for the reaction of the carbocation with nucleophile (H_2O) to give an oxonium ion.

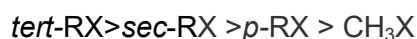
As in the case of S_N2 reaction, the structure of the alkyl halides also affects the rate of the reaction. We are giving the relative rates of reaction of some alkyl bromides under typical S_N1 conditions in Table 13.6.

Table 13.6: Relative reaction rates of hydrolysis of some alkyl bromides under typical S_N1 conditions

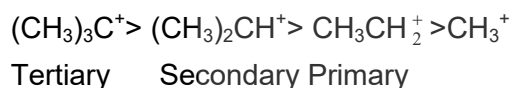
Alkyl bromide	Relative rate
CH ₃ -Br	1.00*
CH ₃ CH ₂ -Br	1.00*
(CH ₃) ₂ CH-Br	11.6
(CH ₃) ₃ C-Br	1.2 × 10 ⁶

*The observed reactions on the methyl or other primary alkyl bromides probably occur by S_N2 route not S_N1 so their relative rates are considered as one.

Therefore, among alkyl halides, the order of relative rates is

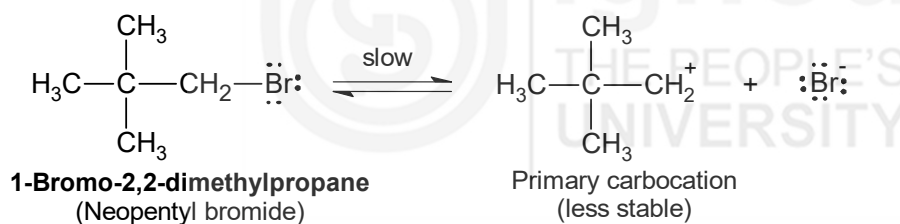


This order is reasonable, since the order of stability of the intermediate carbocation formed in the slow rate determining step is also the same.

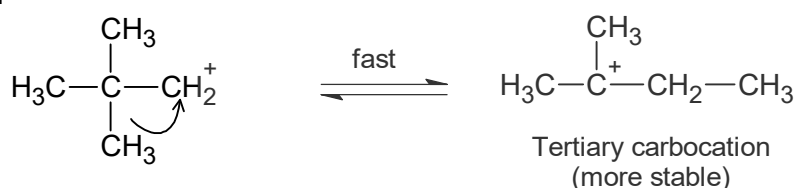


The S_N1 reaction has also been found to be associated with rearrangements. The intermediate carbocation can rearrange to a more stable carbocation. The following is an example of one such rearrangement:

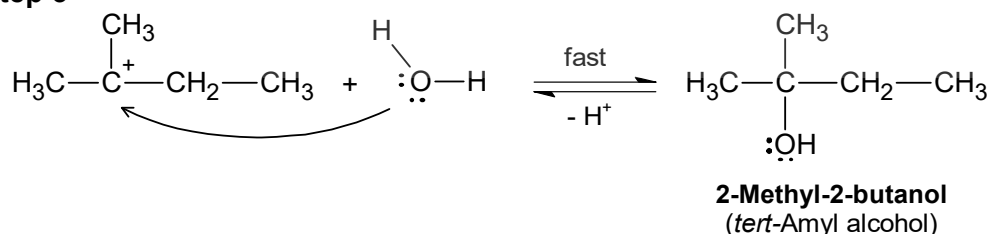
Step 1



Step 2



Step 3

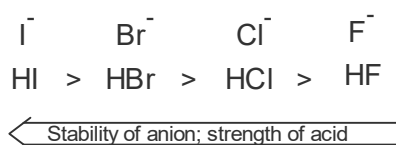


You can notice in step 2, how the primary carbocation rearranges, through the shift of a —CH₃ group, to produce the more stable tertiary carbocation.

After studying both the mechanisms, you can point out some of key differences. First, S_N2 reaction involves a single step and has no intermediate. In contrast, S_N1 reaction has two steps with the formation of intermediate

Among halide ions, iodide anion is having the largest size and is least electronegative, its negative charge is delocalised over the large volume of space, therefore, is the most stable. Thus, HI is the strongest acid of halogen acids. On the other hand, fluoride anion is the smallest ion, its charge is the most concentrated, and fluoride ion is the least stable. Therefore, it is the weakest acid of the halogen acids.

carbocation. S_N2 follows second order kinetics whereas S_N1 follows first order kinetics. S_N2 reaction of an optically active alkyl halide gives product with inversion of the configuration, on the other hand, S_N1 reaction of an optically active alkyl halide gives generally racemic substitution products. In S_N2 reaction, each replacement of hydrogen by an alkyl group decreases the rate of reaction and opposite is observed in S_N1 reaction. Nature of halide group also influences the rate of reaction. We have seen in transition state of both S_N2 and S_N1 reactions that the leaving group develops a partial negative charge. Therefore, the ability of a leaving group is related to how stable it is as an anion. The most stable anions are the best leaving group and the weak conjugate bases of strong acids. Thus on the basis of strength of acids we can determine which anion is best leaving group. For example the order of relative strength of halogen acids and relative stability of halide ions is shown below:



Among halogen acids, the order of strength increases from HF (weakest) to HI (strongest). Thus, the best leaving group among halide is I^- and poorest leaving group is F^- .

In fact, both S_N2 and S_N1 mechanisms can be viewed as the limits of a mechanistic continuum. Beside the nature of alkyl halide there are many factors such as nature of nucleophile, nature of leaving group, solvent system used during reaction etc. which influence the preference of one mechanism over the other. We are not going in detail of these factors at this stage but we present a brief overview useful to predict the type of mechanism that dominates under certain reaction conditions in Table 13.7.

Table 13.7: A summary of S_N2 vs S_N1 reactions

Alkyl Halide	S_N2	S_N1
$\text{CH}_3\text{-X}$	S_N2 reaction is favoured	S_N1 reaction does not occur because of the unstable methyl cation
$\text{RCH}_2\text{-X}$	S_N2 reaction is favoured	S_N1 reaction rarely occurs as the formation of primary carbocation rarely takes place, exceptions are allylic and benzylic carbocations. Allylic and benzylic halides follow both S_N2 and S_N1 mechanisms
$\text{R}_2\text{CH-X}$	S_N2 reaction is favoured in aprotic solvents with good nucleophile	S_N1 reaction is favoured in protic solvents with poor nucleophiles and good leaving groups
$\text{R}_3\text{-X}$ Reaction at chiral centre (optically active centre)	S_N2 reaction does not occur because of steric factor. Inversion of the configuration	S_N1 reaction is favoured because of the ease of formation of tertiary carbocation Racemisation is favoured
Rearrangement reactions	No rearrangements in S_N2 reaction	Rearrangements possible during S_N1 reaction

SAQ 5

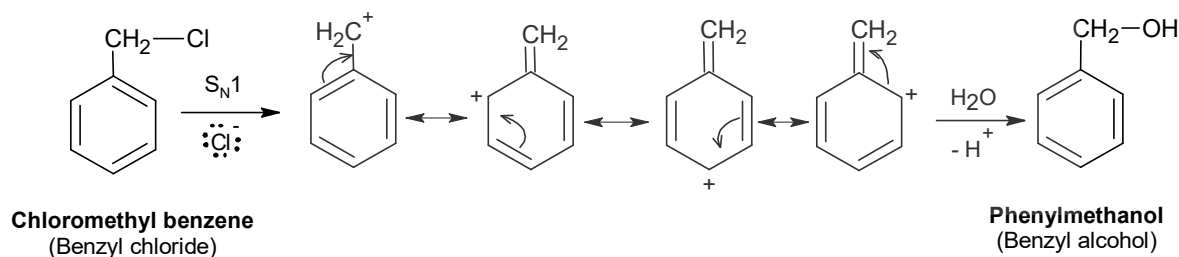
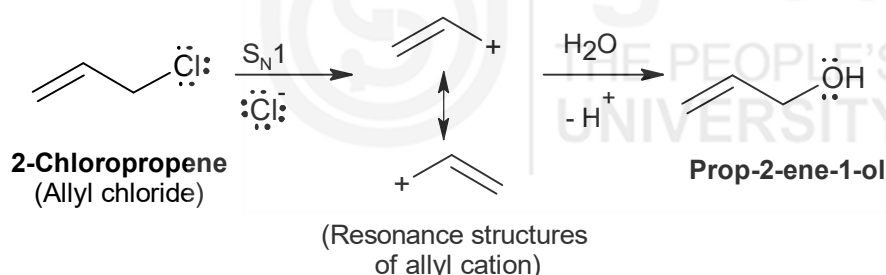
The reaction of 2-bromo-2-methylpropane with azide ion in methanol is a typical S_N1 reaction. What happens to the rate of the reaction if concentration of azide ion is doubled?

Some Typical Nucleophilic Substitution Reactions:

As mentioned above the mechanism of a particular nucleophilic substitution reaction is based on the structure of alkyl halide, nature of nucleophile and leaving group, and solvent. Now we will consider few reactions which support this argument.

Substitution Reactions of Allylic and Benzylic Halides:

The behaviour of substituted alkyl halides such as allylic and benzylic halides in S_N1 and S_N2 reactions deserves to be considered separately. Both these halides are very reactive under both S_N1 and S_N2 conditions. They undergo S_N1 reaction at faster rate than tertiary alkyl halides. The reason for the enhanced reactivity under S_N1 conditions lies in the **resonance stabilisation** of the carbocation intermediate and for S_N2 reaction in the stabilisation of the S_N2 transition state due to charge delocalisation on π bond orbitals. To illustrate this, further let us consider S_N1 reaction of allyl chloride and benzyl chloride with H_2O .



Now, consider the S_N2 reactions. Allylic halides and benzylic halides also undergo S_N2 reaction at a faster rate than primary alkyl halides or even methyl halides. The reason for the greater S_N2 reactivity of allylic and benzylic halides is stability of the transition state. In the case of allylic and benzylic halides partial overlap of the π bond orbitals helps in delocalisation of the negative charge on the transition structure thus increasing the rate of the reaction (see Fig. 13.4).

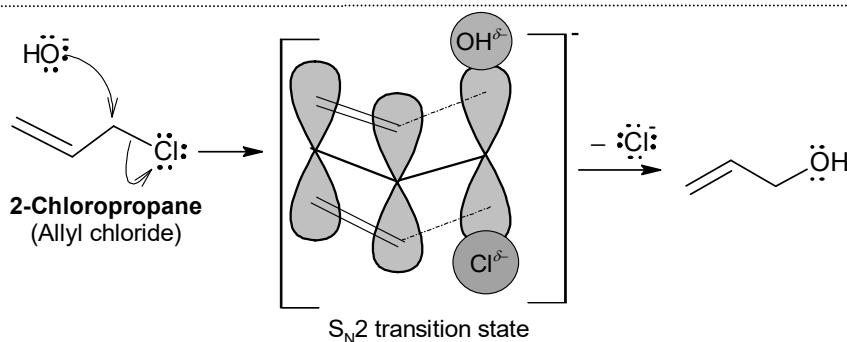
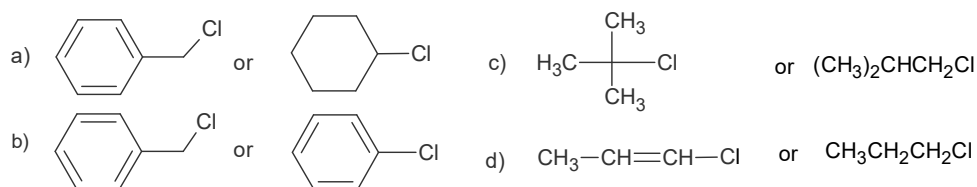


Fig. 13.4: Stabilisation of S_N2 transition state through overlap of the p -orbitals of π bond and p -orbital that formed on rehybridisation of carbon centre.

SAQ 6

Which member of each of the following pairs would undergo the faster S_N2 reaction? Explain your answer.



Hydrolysis of Alkyl Halides

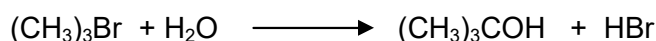
Hydrolysis of alkyl halides can be achieved by simply water or aqueous solution of NaOH and KOH. Methanol or ethanol is also added to the aqueous solution to dissolve alkyl halide.

The reaction between a primary alkyl halide and water is very slow even if they are heated. In this reaction, halogen atom is replaced by $-OH$ through S_N2 mechanism. For example, consider the reaction of typical primary alkyl halide, 1-bromoethane:



With water, nucleophilic substitution is very slow because water is not a very good nucleophile. But if we add hydroxide ion, the hydrolysis will be faster than just water because the hydroxide ion is a more powerful nucleophile. Although water and hydroxide ion are electron pair donors, the hydroxide ion carries a full negative charge which enhances the nucleophilicity of hydroxide ion compared to the electrically neutral water molecule.

Now consider the reaction of a tertiary alkyl halide with water, when it is heated under reflux with water, the halogen is replaced by $-OH$ to give an alcohol. This reaction happens much faster than the corresponding one involving a primary alkyl halide and it follows S_N1 mechanism. For example:



The rate of the overall reaction is governed entirely by how fast the alkyl halide is ionised. In this case addition of hydroxide ion doesn't affect the

reaction rate. The water/ OH^- is not involved in the slow step of the reaction. Thus, this reaction is generally carried out in water in place of aqueous solution of NaOH or KOH. Secondary alkyl halides follow both $\text{S}_{\text{N}}2$ and $\text{S}_{\text{N}}1$ mechanism not as fast as we observed in case of tertiary alkyl halide. This relative reactivity of alkyl halide may be used in identification of primary, secondary and tertiary alkyl halides using alcoholic silver nitrate solution. The tertiary halide produces a precipitate of silver halide almost instantly and the secondary halide gives a slight precipitate after a few seconds. The precipitate thickens up with time. The primary halide may take considerably longer to produce a precipitate. However, aryl halides and alkenyl halides will not react with alcoholic silver nitrate.

Reaction with Cyanide Ion:

Alkyl halide on treatment with a solution of sodium or potassium cyanide in ethanol, gives a nitrile. The cyanide ion is a good nucleophile as there is a formal negative charge and a lone pair on the carbon atom.

For example, using 1-bromobutane as a typical primary alkyl halide:



In this reaction, bromine is simply replaced by a $-\text{CN}$ group by $\text{S}_{\text{N}}2$ mechanism and gives pentanenitrile (Butyl cyanide). A small amount of pentaneisotrile is also formed in the above reaction. Secondary and tertiary alkyl halides also behave similarly, although the mechanism will vary depending on which type of alkyl halide you are using.

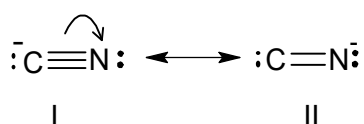
This reaction is very useful as it affords a method of adding one carbon atom to a chain. The resultant nitrile can be either hydrolysed by heating with dilute acid to a carboxylic acid:



or it can be transformed into an amine by reaction with hydrogen at 423 K in the presence of a nickel catalyst:

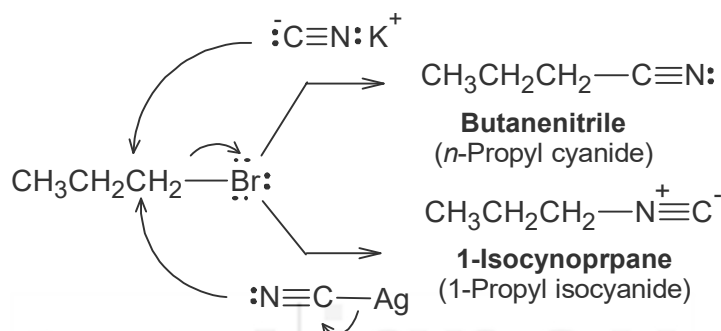


The reaction of AgCN with alkyl halides produces mainly isonitrile, RNC , in contrast to similar reactions discussed above with alkali metal cyanide (NaCN and KCN), which yield mostly nitriles. This is because of the presence of two nucleophilic centres in cyanide ion. In fact cyanide ion has two resonating structures as shown below:



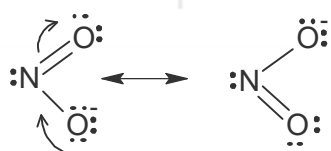
Therefore, it may react either by carbon or nitrogen centre. Such nucleophilic species which have more than one site for reaction are called ambident nucleophiles. Alkali metal cyanides such as NaCN and KCN , are ionic compounds and dissociate as cyanide ion and metal ion. In cyanide ion, carbon centre is a better nucleophile than nitrogen centre because it has full

negative charge besides having a lone pair; therefore, cyanide normally reacts with alkyl halide through its carbon centre and giving nitrile as major product. On the other hand, silver cyanide is predominantly covalent, therefore, silver remain bonded to carbon of cyanide group and leaving the nitrogen end free to be nucleophilic (whereas potassium or sodium ions is not so attached to cyanide ion during reaction). Thus, only nitrogen centre is available for the attack on electrophilic centre of alkyl halide. As a result, alkylisocyanides are formed as main products. Silver cyanide also promotes an S_N1 reaction, as the silver interact with the halide ion, forming carbocation or enhancing carbocation character of transition state. Now comparatively weak nitrogen nucleophilic centre of cyanide ion can attack on such activated carbon centre and forming alkylisocyanide as major product. Products formed during the reaction of 1-bromopropane with potassium cyanide and silver cyanide are shown below.



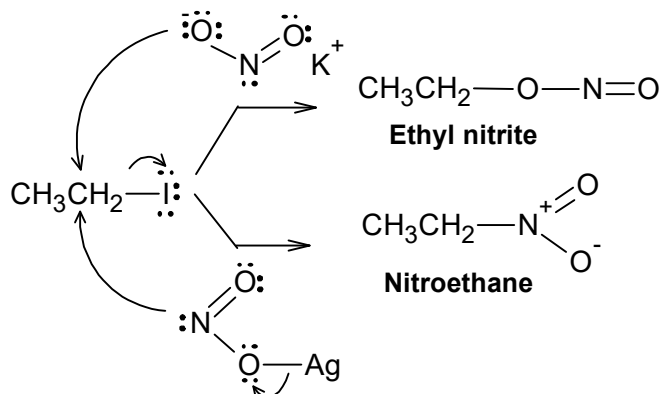
Reaction with Nitrite Ions

Similar to cyanide ion, nitrite ion is also an ambident nucleophile with two different nucleophilic centres, i.e. one through oxygen results formation of alkyl nitrite and other through nitrogen gives nitroalkanes.



Resonance stabilised nitrite ion

Alkyl halides react with alkali metal nitrites i.e. NaNO_2 or KNO_2 to give corresponding alkyl nitrites as the major product along with nitroalkanes as minor product. However, when alkyl halides are treated with silver nitrite (AgNO_2), nitroalkanes are formed as major product.



Alkali metal nitrites (NaNO_2 and KNO_2) are predominately ionic compounds; therefore, nitrite ion attacks mainly through better nucleophilic site i.e. negatively charged oxygen to electrophilic centre of alkyl halide to form alkyl nitrite. On the other hand, silver nitrate is covalent in nature and remains bonded to oxygen atom of nitrite group and leaving the nitrogen end free to be nucleophilic. This nucleophilic nitrogen through its lone pair of electrons attacks and as a result, nitro compounds are formed as major products.

Reaction with Metals

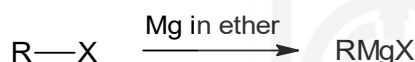
Alkyl halides react with certain metals to give compounds containing carbon-metal bonds. Such compounds are known as organo-metallic compounds.

For example, the reaction of chloroethane with a sodium lead alloy under pressure gives tetraethyllead.

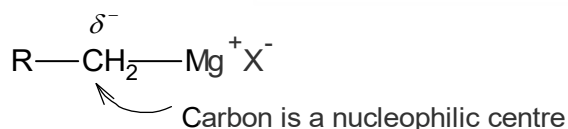


Tetramethyl and tetraethyl-lead are used as anti-knock additives to petrol.

An important class of organo-metallic compounds discovered by Victor Grignard in 1900 is alkyl magnesium halides, RMgX , referred to as Grignard Reagents. These reagents are obtained by the reaction of alkyl halide with magnesium metal in dry ether.



In the Grignard reagent, the carbon-magnesium bond is covalent but highly polar, with carbon pulling electrons from electropositive magnesium and making the carbon atom both nucleophilic and strongly basic; the magnesium-halogen bond is essentially ionic.

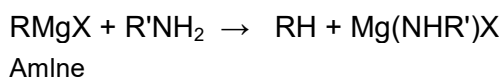
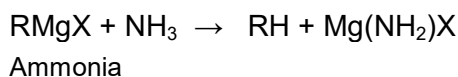
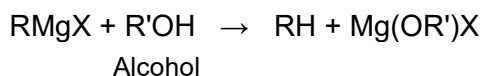
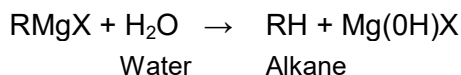


Grignard reagents, therefore, take part in nucleophilic addition reactions.

Grignard reagents are used to prepare a large variety of organic compounds.

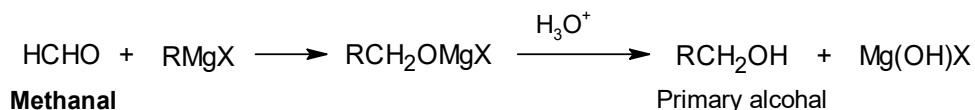
Some of the important reactions are:

- i) Preparation of alkanes:** Alkanes are prepared by the reaction of Grignard reagents with water, alcohols, ammonia, amines etc.:

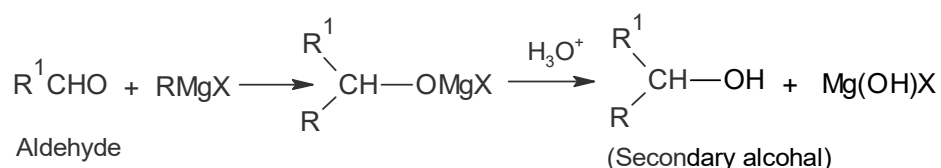


In these reactions Grignard reagents act as very strong bases and react with any source of proton (acid) to give hydrocarbons. It is therefore, necessary to avoid even traces of moisture while using a Grignard reagent.

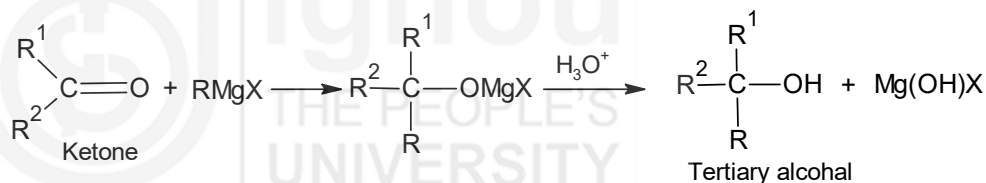
- ii) **Preparation of alcohols:** Primary alcohols are obtained by the reaction of methanal and Grignard reagent followed by treatment with dilute acid:



Secondary alcohols are obtained when a Grignard reagent is treated with any aldehyde (other than methanal) followed by decomposition of the addition product with a dilute acid:



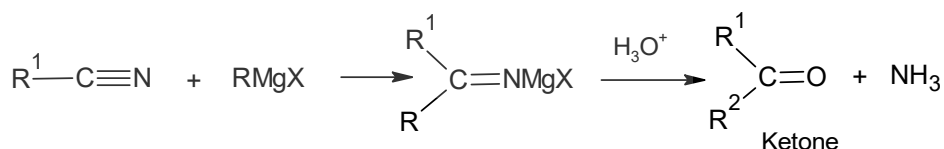
Tertiary alcohols are obtained on treatment of a ketone with Grignard reagent and subsequent addition of dilute acid:



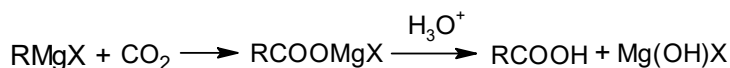
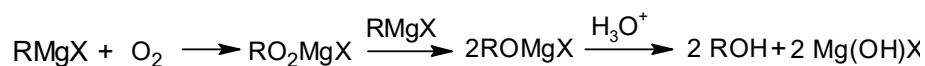
Alcohols are also obtained when epoxides are reacted with Grignard reagent and the addition product is hydrolysed with dilute acid:



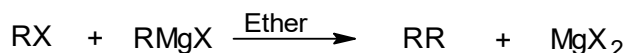
- iii) **Preparation of Ketones:** Ketone can be prepared by the reaction of an alkyl nitrile with a Grignard reagent:



Grignard reagents also react readily with oxygen and carbon dioxide as shown below. These side reactions can be prevented by forming the Grignard reagent under an inert atmosphere such as a nitrogen.



Another side reaction that occurs during the formation of Grignard reagents is the coupling reaction between two alkyl (or aryl) halides as shown below. This side reaction can be minimized if the concentration of the halide is kept low by the slow addition of an ether solution of the halide to a mixture of magnesium and ether.



This reaction is similar to Wurtz reaction which you have studied earlier.

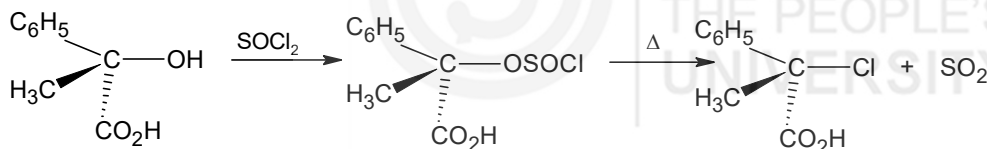
Using the reactions discussed above, attempt the following SAQ.

SAQ 7

How would you prepare primary, secondary and tertiary alcohols? Give one reaction for each case.

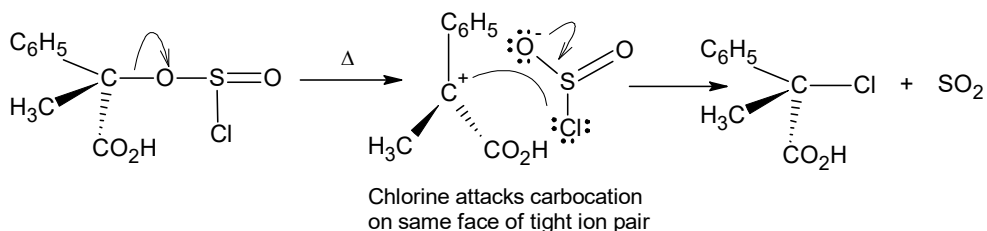
SNi Reaction

So far we have discussed substitution reactions which involve two reactants, a substrate (alkyl halide) and a nucleophile. In some substitution reactions, the nucleophile is a part of the substrate. Such intramolecular substitutions are more rapid than the corresponding intermolecular reactions. Consider following reaction:

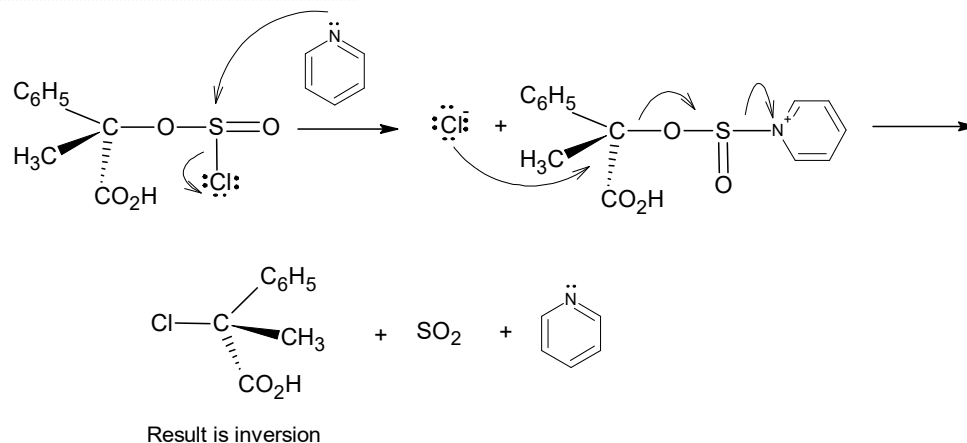


This reaction is said to proceed by S_{Ni} mechanism meaning substitution nucleophilic internal (intramolecular), since both the nucleophile and the leaving group are part of a single molecule. Stereochemistry of these reactions shows retention of configuration at the chiral carbon atom i.e. nucleophile attacks from the same face as the leaving group departure.

The first step is like that an S_N1 reaction, i.e., formation of ion pair. In the second step, a part of the leaving group attacks only from the front side leading to retention of configuration.

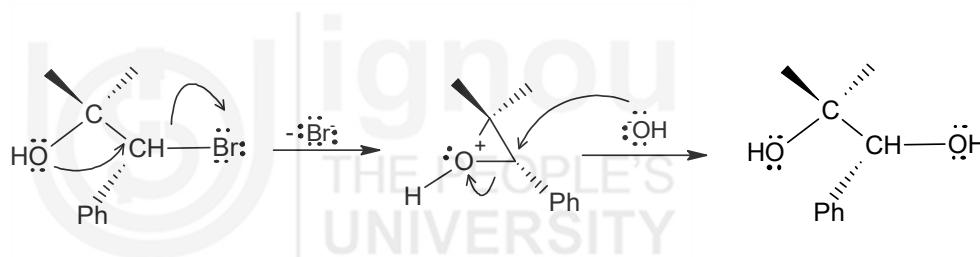


If, however, an external chloride ion is available in the presence of an amine like pyridine, a normal S_N2 reaction occurs in the above case with inversion of configuration.



The S_Ni reaction mechanisms did not meet with wide acceptance, even though in chemical literature this In gold system is still utilised to describe similar types of substitution reactions.

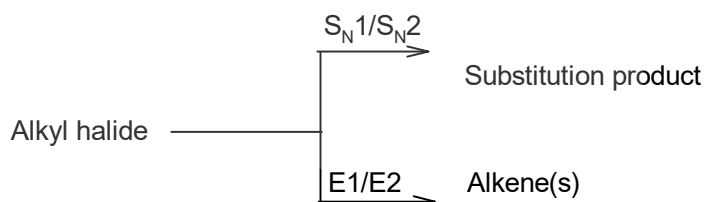
Finally, neighbouring group participation can occur to produce the same result as S_Ni - i.e. overall retention of configuration in product. For example, if the molecule in question has a nucleophilic substituent that can reach the electrophilic site, then that substituent may participate in the reaction as well as the incoming nucleophile. If the electrophilic site is chiral, there will be overall retention rather than inversion, as shown in the following example;



It is worth noting that both steps of this reaction involve the S_N2 mechanism, with inversion, so the overall result (of double inversion) is retention.

Elimination Reactions

A side reaction that occurs during substitution reactions of alkyl halides is the elimination of HX (dehydrohalogenation) to produce an alkene.

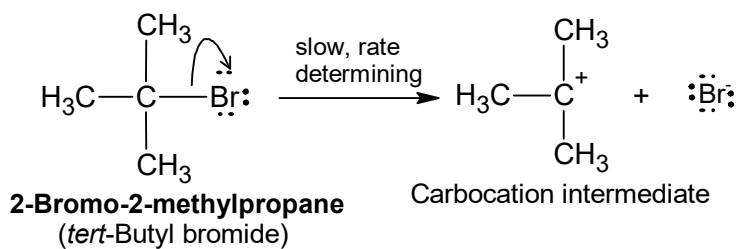


Under appropriate conditions such as the use of a strong base (OH^- or OR^-), and high temperature, elimination can be the principle reaction and thus become a method for the preparing alkenes. We have already introduced such reaction in Unit 16 of first semester course.

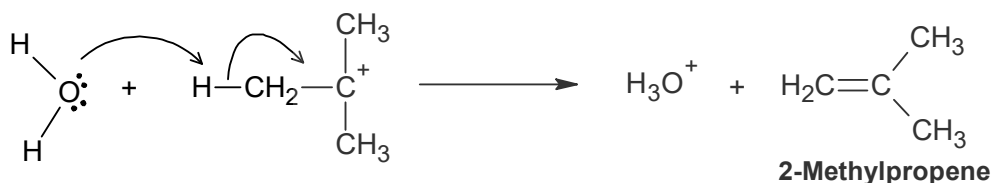
Like the nucleophilic substitution reactions, elimination reactions of alkyl halides can proceed by either a first or a second order mechanism. The first order elimination reaction is symbolised as E1 and the second order elimination reaction as E2.

E1 reaction: In the absence of a strong base tertiary alkyl halides, and to some extent secondary alkyl halides, dehydrohalogenate via the E1 mechanism to give alkenes. The mechanism has two steps.

Step 1 (slow): Ionisation of the C–X bond gives stable carbocation:



Step 2: Proton transfer from carbocation intermediate to form alkene:

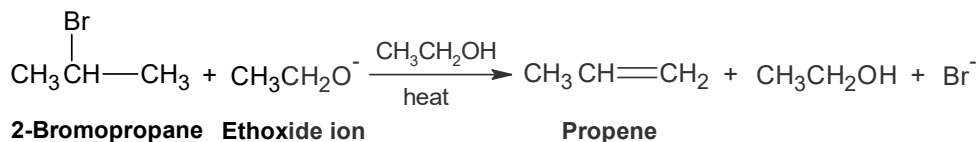


The first step, as in $\text{S}_{\text{N}}1$ reactions is ionisation of the alkyl halide. Since, this is the slow i.e., rate determining step the E1 reaction follows first order kinetics.

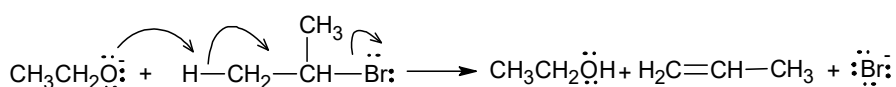
Note that the base here attacks the hydrogen atom and not the carbon carrying the positive charge.

E1 reactions of alkyl halides occur under the same conditions as $\text{S}_{\text{N}}1$ reaction (polar solvent, very weak base etc.) Therefore the E1 reaction is a strong competitor of the $\text{S}_{\text{N}}1$ reaction. The order of reactivity of different halide types is the same in both reactions, that is *tert* > *sec* > *p*. The E1 reaction is favoured by the higher temperature and is most common in tertiary halides.

E2 reaction: The most useful elimination reaction of alkyl halides is the E2 reaction (bimolecular elimination). The E2 reactions of alkyl halides are favoured by the use of strong bases, such as OH^- or OR^- and high temperature. Typically the E2 reaction is carried out by heating the alkyl halide with KOH or $\text{NaOCH}_2\text{CH}_3$ in ethanol.

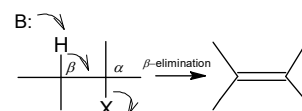


A mechanism consistent with the rate-law is given below, in which the proton and the halide ion are removed simultaneously to give the alkene i.e. bond breaking and bond forming are concerted.

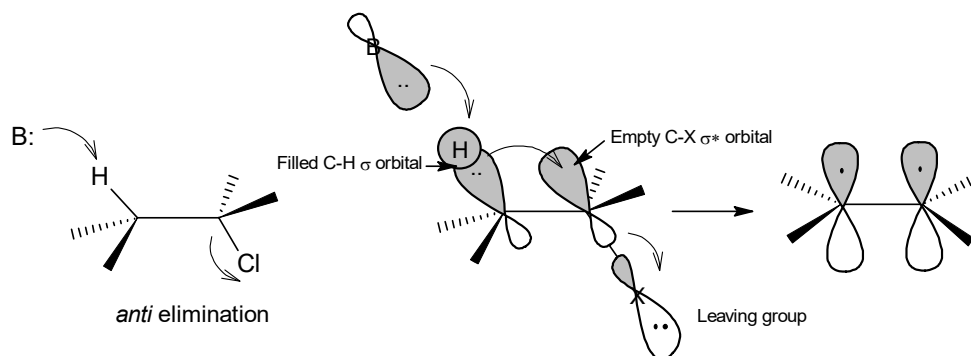


Stereochemical studies reveal that E2 elimination reactions are stereoselective *anti*-eliminations. The anti-elimination involves all backside electronic displacements.

E2 elimination reaction is an example of β -elimination. In a β -elimination reaction two groups are eliminated from adjacent atoms. It is by far the most common type of elimination reaction in organic chemistry.



Backside attack of the base on the C-X bond



Similar to S_N2 reactions, there is an orbital-based reason for the anti-elimination. This can be explained using molecular orbital approach. You can see in above diagram that filled C-H σ bonding molecular orbital aligned with the empty C-X σ^* antibonding molecular orbital. As the strong base removes the proton, the two electrons move from C-H σ bonding orbital to empty C-X σ^* antibonding orbital and thereby breaking the C-X bond. This anti and coplanar arrangement of the molecular orbitals leads to proper phasing to form new π bond.

Substitution versus Elimination

We have said earlier that substitution and elimination are competitive reactions; one reaction occurs at the expense of the other. Now, we consider the important factors which determine the direction of the reaction.

- The structure of the alkyl halide,
- The nature of the base, and
- Temperature.

We have summarized the effect of these variables in Table 13.8.

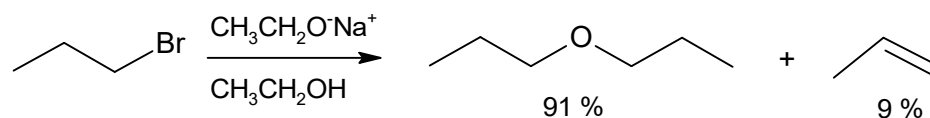
Table 13.8: Substitution versus Elimination

Alkyl Halide	Weak base	Moderate base	Strong base
Primary Alkyl halide	S_N2	S_N2	S_N2 with good nucleophile and E2 with poor nucleophile and high temperature
Secondary Alkyl halide	S_N1 or S_N2 ; Some E1 at high temperature	S_N2 ; E2 at high temperature	E2
Tertiary Alkyl halide	S_N1 and E1; E1 predominates at higher temperature	E2	E2

In general, branching in alkyl halides and higher temperature increases the ratio of elimination to substitution.

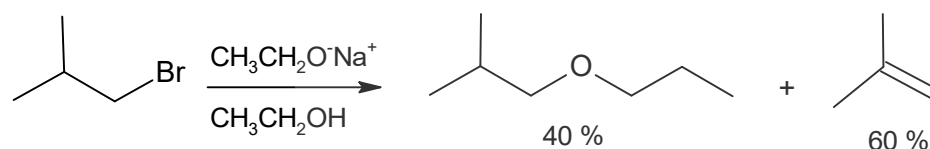
To further understand effect of above factors, we will now consider some specific examples and analyse the factors that determine the direction of the reaction.

Example 1



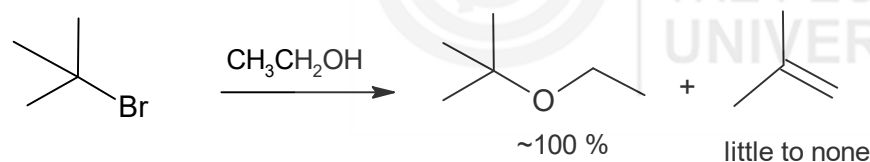
In above example alkyl halide is primary and therefore the major reaction is S_N1 and $E1$ is a minor reaction. Further, ethoxide ion is strong base as well as a good nucleophile, therefore, S_N2 reaction dominated over $E2$ reaction.

Example 2



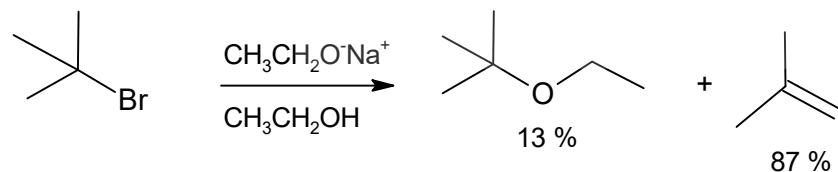
Because of branching in primary alkyl halide (steric factor) in this case this will give nearly equal amount of S_N2 and $E2$ reactions. Similar reaction with secondary alkyl halides will be dominated by $E2$ reaction.

Example 3

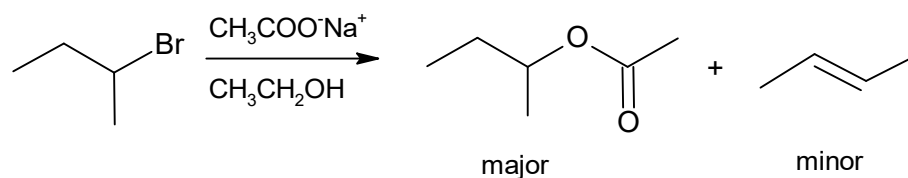


Here, ethanol is a weak base i.e. weak nucleophile and alkyl halide is tertiary, therefore S_N2 and $E2$ reaction can easily be ruled out. It is expected that this reaction will follow S_N1 and $E1$. Generally, $E1$ only is a minor reaction.

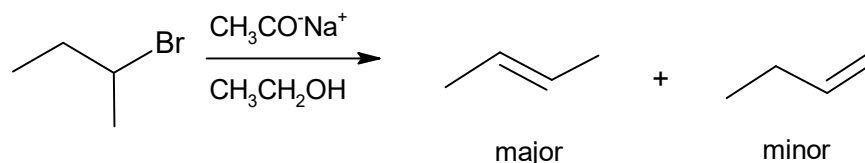
The reaction of the same alkyl halide with strong base such as sodium ethoxide in ethanol, follows $E2$ reaction predominantly.



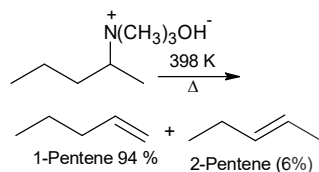
Example 4



This reaction alkyl halide is secondary and acetate ion is weak base. Therefore, there will be little or no E2 reaction. This reaction predominantly follows S_N2 reaction. If same alkyl halide is treated with strong base such as NaOC_2H_5 in ethanol, E2 would have been the dominated reaction.

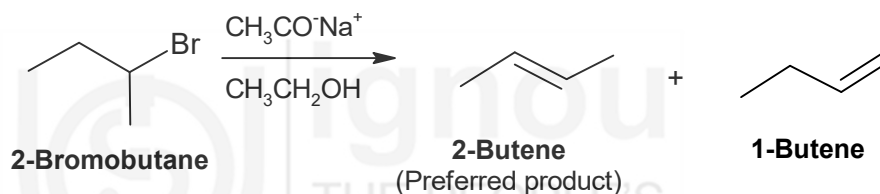


Elimination reaction in quaternary ammonium hydroxides ($\text{R}_4\text{N}^+\text{OH}^-$) does 'not follow Saytzeff rule, but they undergo elimination reactions and yield the Hofmann product, the alkene with fewer alkyl groups on the π -bonded carbons. Such reactions are known as Hofmann eliminations and follow E2 mechanism. The formation of the less substituted less stable alkene can be attributed to steric hindrance in the transition state stability (relative transition state energies) due to the group, e.g., butyl in the example given below:



In this above reaction, formation of more substituted alkene is dominated over less substituted alkene. More substituted alkene is thermodynamically more stable than the less substituted alkene. Hence, products of such reaction are governed by the relative stability of products. In β -elimination reactions, relative stability of products provides a rationale for the Saytzeff rule of regiochemistry. Now, let us discuss this rule.

Saytzeff rule: In the alkyl halides, where the halogen is not attached to the terminal carbon atom, elimination is possible in two directions, giving two isomeric alkenes. An illustrative example is the dehydrobromination of 2-bromobutane to give 1- and 2-butenes:

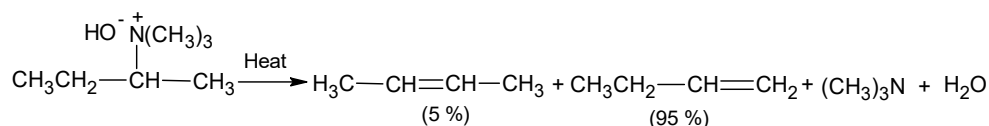


In the above reaction, the major product is 2-butene. This follows the rule formulated in 1875 by Alexander Saytzeff. Saytzeff rule states that in a dehydrohalogenation reaction of alkyl halides, **the major product will be the one that has the more alkyl groups attached to the resultant carbon-carbon double bond**. The rule parallels the order of thermodynamic stability of the alkenes; that is, the alkene with more alkyl groups attached to the carbon-carbon double bond is more stable. The order of stability of alkenes may be represented as:



Because of the relative stability of the resultant alkenes, tertiary halides undergo dehydrohalogenation more readily than secondary halides, which dehydrohalogenate more readily than primary halides (as we have already noticed earlier).

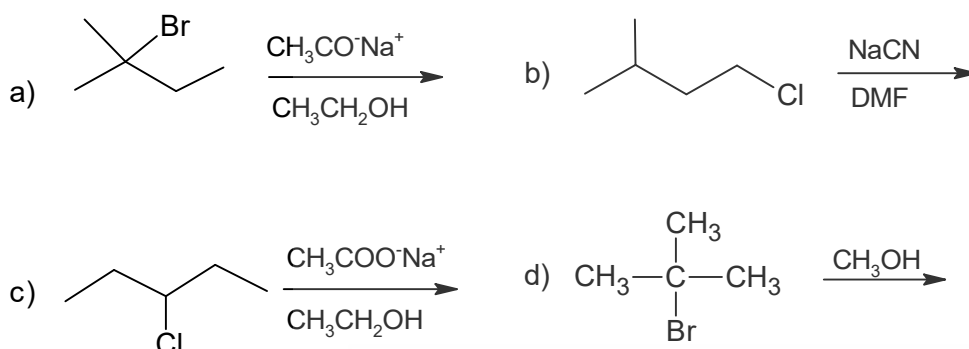
Exceptions to the Saytzeff rule are exemplified by the Hofmann rule. This rule predicts that β -elimination will occur preferentially to give the less substituted alkene as major product. For example thermal decomposition of *sec*-butyltrimethylammonium hydroxide gives 1-butene as the major product.



If there are more than one β -hydrogen is anti to leaving group, then there will be competition between Hofmann and Saytzeff elimination. Eliminations involving halide ions or negative charged leaving groups generally follow Saytzeff rule, unless a bulky base is used. On the other, if leaving group is neutral in nature such as $N(CH_3)_3$ and $S(CH_3)_2$, the eliminations will follow Hofmann rule. Bulkier bases such as $(CH_3)_3COK$ also predominantly give Hofmann product. The regioselectivity of β -elimination can be explained on the bases of relative stability of transition state during elimination reaction.

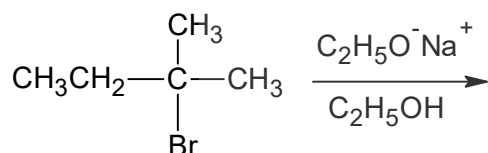
SAQ 8

Predict whether each reaction proceeds predominantly by S_N1 or S_N2 or $E1$ or $E2$.



SAQ 9

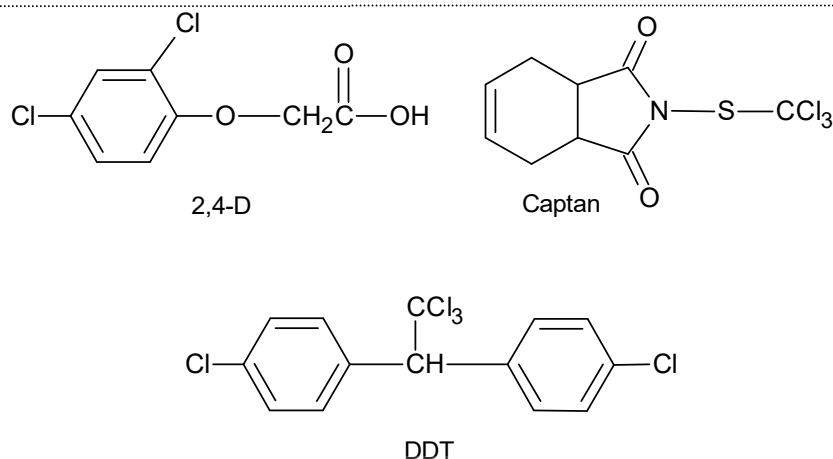
Write the equation for the formation of alkenes from the following starting material. If you expect more than one product, indicate which alkene is the major product.



13.4.5 Uses of Alkyl Halides

Alkyl halides find a variety of uses and applications in our everyday lives. They are used in labs as synthetic intermediate compounds and as solvents. Dichloromethane (CH_2Cl_2 , methylene dichloride), trichloromethane (CHCl_3 , chloroform), tetrachloromethane CCl_4 , carbon tetrachloride) and trichloroethylene ($\text{Cl}_2\text{C}=\text{CHCl}$), for example, are used as solvents.

In agriculture, alkyl halide such as 2,4-D applied as herbicides captan as fungicides. The insecticide DDT (1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane) is effectively used to control many diseases such as malaria, typhus, and cholera. Most countries have banned the use of DDT. Since DDT accumulates in fatty tissue of warm-blooded animals (and humans), it was suspected to be carcinogenic. Latter, this assumption has been proven not to be correct.



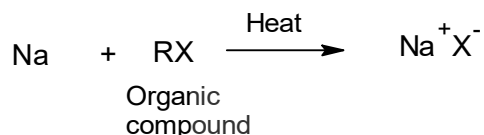
Until the mid-1980s, chlorofluorocarbons (CFCs) were produced in large quantities. They are derivatives of methane and ethane. Freons such as trichlorofluoromethane (freon-11), tetrafluoromethane (freon-14) and trichlorotrifluoroethane (freon-113), for example, are relatively simple CFCs in which all hydrogen atoms have been substituted by chlorine or fluorine atoms. They are prepared by the action of hydrogen fluoride on tetrachloromethane (carbon tetrachloride), trichloromethane and hexachloroethane. CFCs are produced at a reasonable price and are stable, non-toxic, non-inflammable, and non-corrosive. Therefore, CFCs were considered perfect materials for usage in many practical applications, including propellants, coolants in refrigerators and fire-extinguishing agents. Unfortunately, due to their high chemical stability, CFCs have been identified as a severe environmental liability. They are a main cause of ozonolysis in the stratosphere and are largely responsible for the ozone hole. As a result, the production of CFCs is prohibited worldwide. However, due to their high stability, the CFC concentration in the stratosphere will not considerably decrease to a safe level until the year 2050. Now, CFCs are replaced by third generation products such as hydrofluorocarbons (HFCs). They do not harm the ozone layer as much but these products more expensive to produce than CFCs.

Tetrafluoroethene ($\text{CF}_2=\text{CF}_2$) on polymerisation gives a plastic **Teflon**. It is unaffected by chemical reagents, even by boiling aqua regia. It is widely used as a liner in frying pans and on other utensils and tools to provide nonsticking surfaces. Polychlorofluoroethenes are used as oils and greases. Perfluoroheptane is used in the separation of uranium isotopes. Poly(chloroethene) or polyvinyl chloride (PVC) is a plastic material of commercial importance.

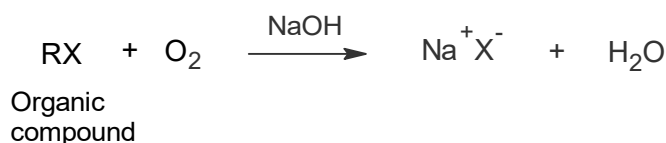
At present, more than 15,000 halogenated organic compounds are produced for industrial purposes. They are used as feedstock for the production of PVC, industrial lubricants, pesticides, insecticides, herbicides, solvents and many others. However, the fact that many of these compounds are either not at all or only barely biodegradable has serious implications on health and environment. Simple compound, carbon tetrachloride used as a fabric cleaner is known to cause damage to liver. Similarly, chloroform a popular anesthetic has been proven to be cancerous. Therefore, use and circulation of alkyl halides has been restricted to some extent.

13.5 LAB DETECTION

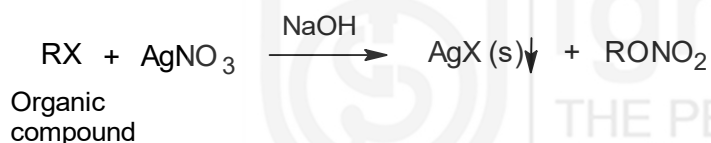
The presence of halogen in an organic compound is readily detected by the **Beilstein test**. In this test a small amount of the compound is placed on a small loop of copper wire, and the loop heated in a flame. A green flame is evidence of the presence of halogen. To ascertain which halogen is present, the covalently bonded halogen has to be converted to the halide ion which can then be identified by the usual methods of inorganic qualitative analysis. This is done by two methods; through sodium fusion (treatment with hot molten sodium metal):



or through Schoniger oxidation by oxygen gas under alkaline condition



In alkyl halides, benzyl halides and allyl halides the presence of halogen can be detected by warming the organic compound with alcoholic silver nitrate. The silver halide formed can be analysed further.



However, aryl halides and alkenyl halides will not react with alcoholic silver nitrate.

The reaction helps in distinguishing alkyl halides from aryl and alkenyl halides.

13.6 SUMMARY

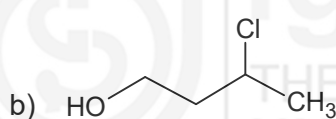
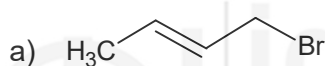
In this unit, we have described the chemistry of alkyl halides. We are summarising below what we have studied:

- Substitution of one or more hydrogen atoms in alkanes by a halogen atom(s) gives rise to alkyl halides. Monohalogen derivatives of alkyl halide can be further classified as primary, secondary and tertiary halides depending on the alkyl group to which halogen is attached.
- Alkyl halides can be prepared from alcohols, from alkanes, from Grignard reagents and through halogenation of hydrocarbons in the presence of light or heat and catalysts.
- The halogen in alkyl halides can be replaced by various nucleophiles. These reactions occur by two different pathways, S_N1 and S_N2 . Benzyl and allyl halides are more reactive than alkyl halides. Aryl and vinyl halides are least reactive and they do not follow S_N2 and S_N1 paths. The reactivity order of halides is allyl > benzyl > alkyl > aryl or vinyl.

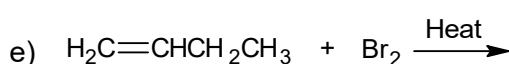
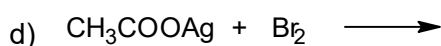
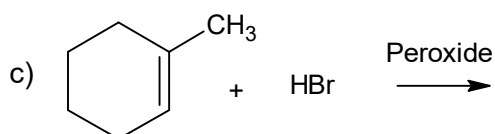
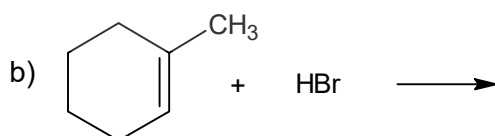
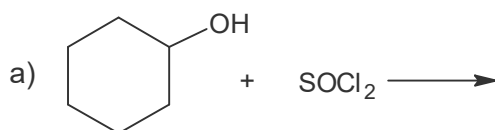
- Alkyl halides undergo elimination reaction (dehydrohalogenation) to give alkenes. These reactions occur by the E1 or E2 pathway. If the halides are such that the loss of a hydrogen on adjacent carbon (β -hydrogen) can occur from either side, isomeric alkenes are formed. Usually, the most stable i.e. more highly substituted alkene is formed as the major product (Saytzeff rule).
- Alkyl halides react with magnesium to form alkyl magnesium halides, called the Grignard reagents. They are very reactive compounds and take part in many reactions to give alkanes, alcohols (primary, secondary and tertiary), ketones and carboxylic acids, etc.
- The halogen derivatives are very useful in industry. The chloro compounds are powerful insecticides and moth repellants. The chlorofluoro compounds (Freons) are refrigerants, aerosol and propellants. Polymerisation of vinyl chloride and tetrafluoroethylene gives plastic in the name PVC and teflon, respectively.
- The halogen can be detected as halide ion.

13.7 TERMINAL QUESTIONS

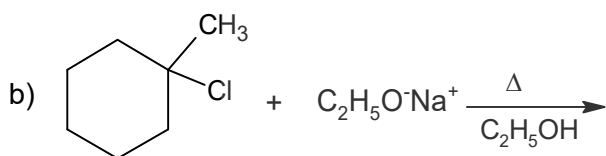
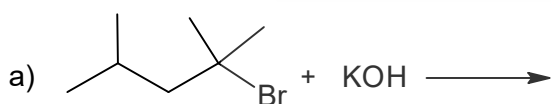
1. Write IUPAC names of the following:



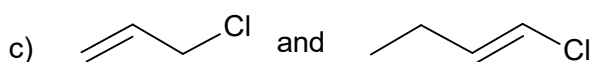
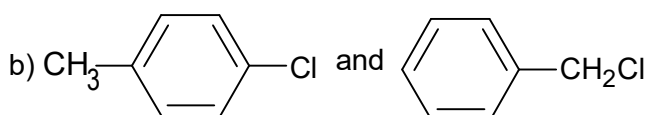
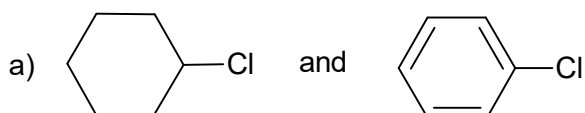
2. Write the possible isomers for molecular formula C_4H_9Cl . Give IUPAC name for each isomer and also classify them as primary, secondary and tertiary.
3. Write the products of the following reactions:



- f) $\text{CH}_3\text{Br} + \text{AgF} \longrightarrow$
4. Among the following pairs of alkyl halides which would undergo $\text{S}_{\text{N}}2$ reaction faster:
- 3-Chloro-1-butene and 4-Chloro-1-butene
 - 1-Iodopropane and 1-Chloropropane
5. Write the equations for the following reactions:
- $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Br} + \text{NaOH (aq)} \rightarrow$
 - $\text{C}_6\text{H}_5\text{CH}_2\text{Cl} + \text{H}_2\text{O} \rightarrow$
 - $\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{NaSH} \rightarrow$
6. Complete the equations given below:
- $\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{CH}_3\text{CH}_2\text{O}^-\text{Na}^+ \rightarrow$
 - $\text{C}_6\text{H}_5\text{CH}_2\text{Cl} + \text{AgNO}_3 \rightarrow$
 - Chlorobenzene + $\text{AgNO}_3 \rightarrow$
7. a) Reaction of 1-Bromopropane with sodium cyanide
 b) Reaction of 1-Bromopropane with silver cyanide
 c) Reaction of 1-Bromopropane with sodium nitrite
 d) Reaction of 1-Bromopropane with silver nitrite
8. Complete the equation for each of the following reactions and if more than one product is formed, indicate which one is major.



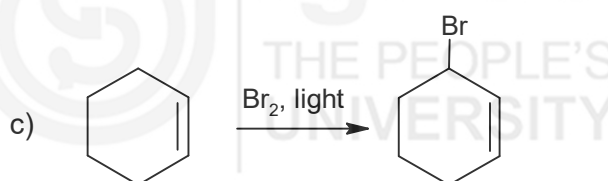
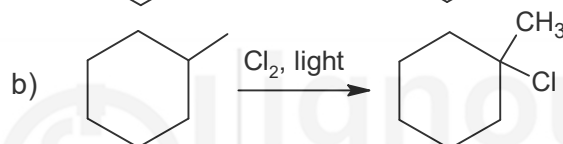
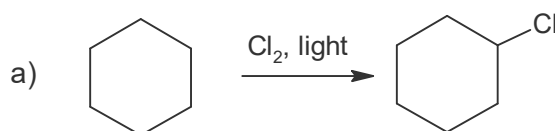
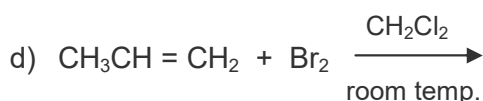
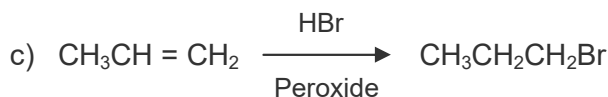
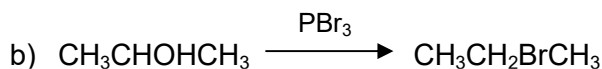
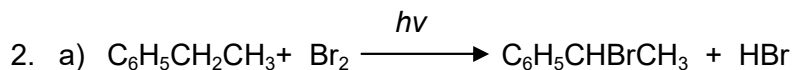
9. Name a simple chemical test or reagent which will readily distinguish between each of the following pair of compounds.



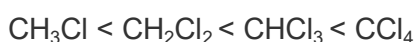
13.8 ANSWERS

Self Assessment Questions

1. a) Secondary alkyl halide, 2-chloro-4-Methylpentane; b) Secondary alkyl halide, 3-Bromopentane; c) Primary alkyl, 1-Chloro-2,2-dimethylpentane; b) tertiary alkyl halide, 2-Chloro-2,4-dimethylpentane.

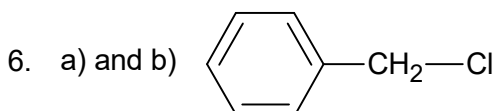


4. Increasing order of boiling point of following alkyl halides:



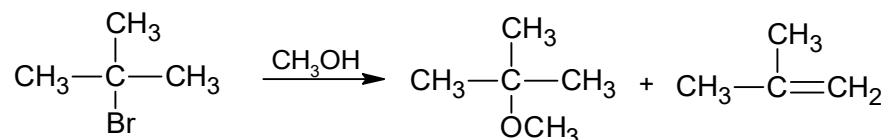
Since molecular mass and size of compounds is also increasing in the same order.

5. The reaction of 2-bromo-2-methylpropane with azide ion follows $\text{S}_{\text{N}}1$ reaction; therefore rate of reaction is proportional to concentration of alkyl halide, so the increase concentration of azide ion does not have much effect on the rate of the reaction.

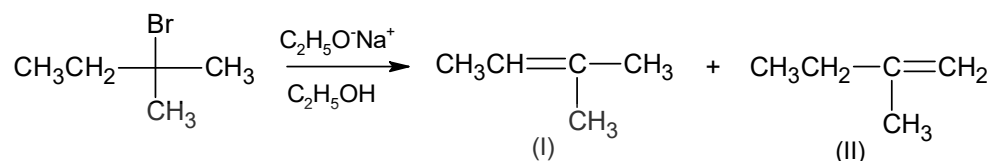


In both a) and b) cases (Chloromethyl)benzene (benzyl chloride) undergoes $\text{S}_{\text{N}}2$ reaction at **faster** rate than chlorocyclohexane and chlorobenzene. The reason for greater $\text{S}_{\text{N}}2$ reactivity of (chloromethyl)benzene is the stability of transition state. Further, the low reactivity of chlorobenzene is attributed to the stronger Ar—Cl bond.

(SN1) and elimination (E1) products. It is difficult to predict the ratio of substitution to elimination products for such reactions.



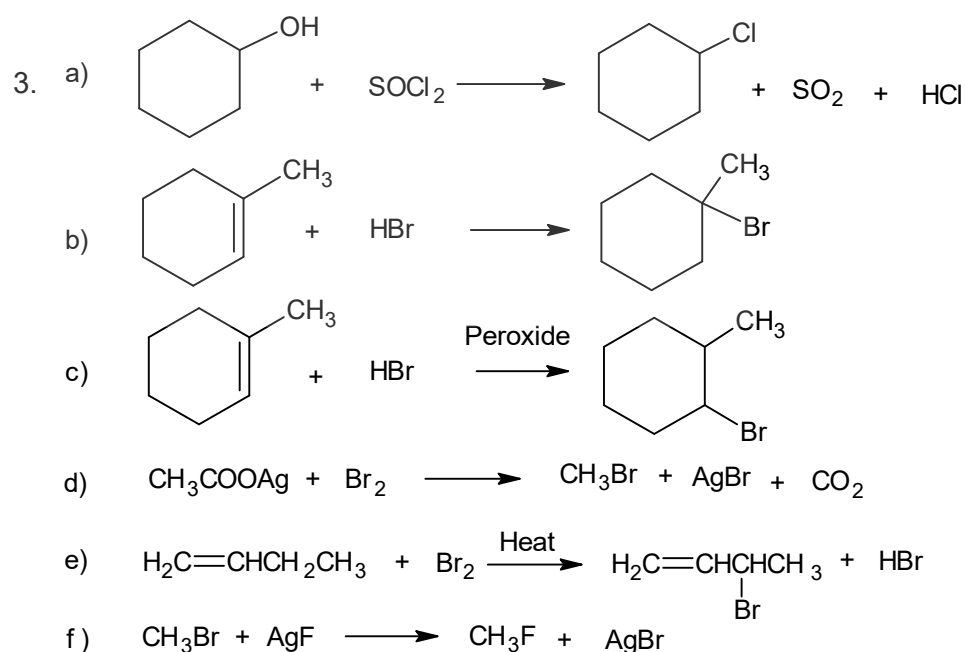
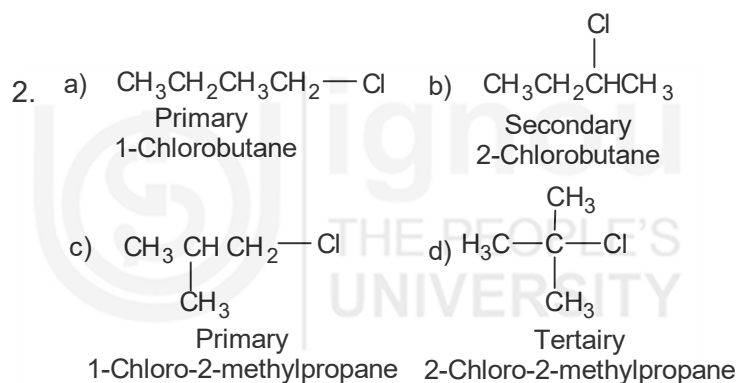
9. Over all reaction can be written as:



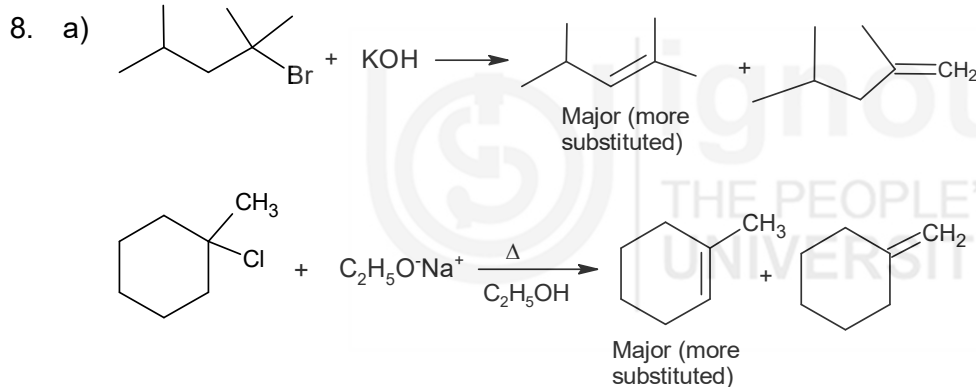
Two products are formed in this case, one (I) is three alkyl substituted alkene and the other (II) is two alkyl substituted, therefore, according to Saytzeff rule (I) alkene will be the major product.

Terminal Questions

1. a) 4-Bromo-2-butene; b) 3-Chloro-1-butanol; c) 1-bromo-3-chloropropane.



4. a) 3-Chloro-1-butene will undergo S_N2 reaction at faster rate as it is an allyl alkyl halide.
- b) 1-Iodopropane as iodine is better leaving group because of its larger size. It will be released at a faster rate on the attack of a nucleophile.
5. a) $\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{NaOH}(\text{aq}) \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2\text{OH} + \text{NaBr}$
- b) $\text{C}_6\text{H}_5\text{CH}_2\text{Cl} + \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_5\text{CH}_2\text{OH} + \text{HCl}$
- c) $\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{NaSH} \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2\text{SH} + \text{NaBr}$
6. a) $\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{Na}^+\text{OCH}_2\text{CH}_3 \rightarrow \text{CH}_3\text{CH}=\text{CH}_2 + \text{CH}_3\text{CH}_2\text{OH} + \text{NaBr}$
- b) $\text{C}_6\text{H}_5\text{CH}_2\text{Cl} + \text{AgNO}_3 + \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_5\text{CH}_2\text{OH} + \text{AgCl}$
- c) Chlorobenzene + $\text{AgNO}_3 + \text{H}_2\text{O} \rightarrow$ no reaction.
7. a) Butanenitrile
- b) Propylisocyanide
- c) 1-Nitropropane
- d) Propylisocyanide



9. Following pairs can be distinguished by the action of alcoholic AgNO_3 reagent with the halides.
- a) With alcoholic AgNO_3 chlorobenzene will not react
- b) Aryl halide (4-Chlorotoluene) also will not react with alcoholic AgNO_3 ,
- c) $\text{CH}_3\text{CH}_2\text{CH}=\text{CHCl}$ also will not react with AgNO_3 .