8.5 Reduction of Alkenes: Hydrogenation

Hydrogenation
• Addition reaction process by which alkenes are reduced to alkanes

Reduction
• Increases electron density on carbon by
  - Forming C-H
  - Breaking C-O, C-N, or C-X bond

A reduction:

\[
\text{C} = \text{C} \quad + \quad \text{H}_2 \quad \xrightarrow{\text{Catalyst}} \quad \text{C} - \text{C} \quad + \quad \text{H}_2
\]

An alkene
An alkane

Reduction of Alkenes: Hydrogenation

Catalytic hydrogenation
• A heterogeneous process that takes place on the surface of insoluble catalyst particles
• Common catalysts for alkene hydrogenation:
  - Platinum – PtO$_2$ (Adams’ Catalyst)
  - Palladium – very fine powder supported on inert material such as charcoal (Pd/C)
• Occurs with syn stereochemistry
  - Both hydrogens add to the double bond from the same side

Mechanism of catalytic hydrogenation

- Alkenes hydrogenated on the catalyst surface and then desorb.
- The product alkenes are then the reaction mixture.
- Hydrogen is then removed under pressure.
- Products are then desorbed from the catalyst surface.

Reduction of Alkenes: Hydrogenation

1,2-Dimethylcyclohexene

 cis-1,2-Dimethylcyclohexane (82%)

H$_2$, PdO$_2$
CH$_2$CO$_2$H

Other unsaturated functional groups are much less reactive toward catalytic hydrogenation under normal reaction conditions.

Reduction of Alkenes: Hydrogenation

Hydrogenation

- Unsaturated vegetable oils reduced to produce saturated fats used in margarine and cooking products
  - Vegetable oils
    - Triesters of glycerol, HOCH₂CH(OH)CH₂OH, with three long-chain carboxylic acids called fatty acids
  - Fatty acids
    - Polyunsaturated carboxylic acids containing long hydrocarbon chains
    - Double bonds have cis stereochemistry

Catalytic hydrogenation of polyunsaturated fats
Catalytic hydrogenation of polyunsaturated fats
- Complete hydrogenation leads to saturated fatty acids
- Incomplete hydrogenation results in isomerized trans fats that release trans fatty acids upon digestion, increasing blood cholesterol levels

Biological hydrogenation (reduction) of isolated double bonds
- Double bond must be adjacent to a carbonyl group
- The reduction of isolated double bonds is rare in biological pathways
- Process occurs in two steps
  1. NADPH (coenzyme reduced nicotinamide adenine dinucleotide phosphate) adds hydride ion ($H^-$) to double bond to produce an anion
  2. Protonation of an anion by acid HA leading to an overall addition of $H_2$

Biological reduction of double bond in trans-Crotonyl ACP leads to the formation of Butyryl ACP

Oxidation
- A reaction that results in a loss of electron density by carbon
- Decreases electron density on carbon by
  - Breaking C-H bond
  - Forming C-O, C-N, or C-X bond

Note: oxidation often adds oxygen; reduction often adds hydrogen
Alkenes on treatment with a peroxyacid, $\text{RCO}_3\text{H}$, are oxidized to give **epoxides**

**Epoxide** (oxiranes)
- Cyclic ethers with an oxygen atom in a three-membered ring

![Chemical reaction image]

**Oxidation of Alkenes: Epoxidation**

**Synthesis of epoxides from alkenes**
- Peroxyacid transfers oxygen to alkene
- Syn stereochemistry
  - Both C-O bonds form on the same face of the double bond
- One step mechanism
- No intermediates

![Chemical reaction image]

**Oxidation of Alkenes: Epoxidation**

**Synthesis of epoxides from halohydrins**
- Preparation of halohydrin through electrophilic addition of HO-X to alkene
- Treatment of halohydrin with base deprotonates OH
  - $\text{O}^-$ nucleophile reacts with C-Cl electrophile substituting C-O bond for C-Cl bond
- Cl\(^-\) eliminated yielding the epoxide

![Chemical reaction image]
Epoxides in biological pathways:
- Epoxides prepared from alkenes as intermediates
- Peroxyacids are not involved
  - FADH₂ used in biological reactions
- Conversion of squalene into 2,3-oxidosqualene; a key step in the biosynthesis of steroids

### Oxidation of Alkenes: Epoxidation

Hydroxylation:
- The addition of an –OH group to each of the two double-bond carbons
- Two step process:
  1. Epoxidation
  2. Hydration
    - Epoxides undergo an acid-catalyzed reaction with water to give corresponding 1,2-dialcohol, or diol

8.7 Oxidation of Alkenes: Hydroxylation

Acid catalyzed epoxide-opening takes place by:
1. Protonation of the epoxide increasing the electrophilicity of carbon
2. Nucleophilic addition of water followed by deprotonation
   - Trans-1,2-diol formed
Hydroxylation in the Laboratory
- Carried out directly by oxidation of an alkene with osmium tetroxide, OsO₄
- Catalytic amount of OsO₄ used in the presence of stoichiometric amount of N-methylmorpholine N-oxide (NMO)
- Syn stereochemistry
- No carbocation intermediate
- Occurs through cyclic osmate intermediate

Oxidation of Alkenes: Hydroxylation

Oxidation of Alkenes: Cleavage to Carbonyl Compounds

Ozone (O₃) is useful double-bond cleavage reagent
- Ozone is generated by passing a stream of oxygen through a high-voltage electrical discharge
- Ozone adds rapidly to C=C bond at low temperature to give molozonide which spontaneously rearranges to ozonide
- Ozonide is treated with reducing agent to convert it to carbonyl compounds

8.8 Oxidation of Alkenes: Cleavage to Carbonyl Compounds

Oxidation of Alkenes: Cleavage to Carbonyl Compounds

- If tetrasubstituted double bond is ozonized, two ketone fragments result
- If a carbon of the alkene is bonded to hydrogen, ozonolysis will cleave the double bond to yield an aldehyde
Potassium permanganate (KMnO₄) in neutral or acidic solution cleaves alkenes to give carbonyl-containing products:

- If a carbon of the alkene is bonded to hydrogen, a carboxylic acid is produced.
- If a carbon of the alkene is bonded to two hydrogens, CO₂ is formed.

\[
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}=\text{CH}_2 + \text{KMnO}_4 \xrightarrow{\text{H}_2\text{O}^+} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{COH} + \text{CO}_2
\]

3,7-Dimethyloct-1-ene \rightarrow 2,6-Dimethylheptanoic acid (45%)

Alkenes are also cleaved by hydroxylation to a 1,2-diol followed by treatment with periodic acid, HIO₄.

- If the two –OH groups of the diol are in an open chain, two carbonyl compounds result.
- If the two –OH groups of the diol are on a ring, a single, open-chain dicarbonyl compound is formed.

\[
\begin{align*}
\text{A 1,2-diol} & \quad \xrightarrow{\text{HIO}_4, \text{aq}} \quad \text{Cyclic peroxide intermediate} \\
\text{A 1,2-diol} & \quad \xrightarrow{\text{HIO}_4, \text{aq}} \quad \text{Cyclopentanone (87%)}
\end{align*}
\]

**Worked Example 8.3**

**Predicting the Reactant in an Ozonolysis Reaction**

What alkene would yield a mixture of cyclopentanone and propanal on treatment with ozone followed by reduction with zinc?

\[
\begin{align*}
\text{1. } \text{O}_3 & \quad \xrightarrow{\text{2. Zn, acetic acid}} \\
\text{7} & \quad \xrightarrow{\text{1. O}_3} \quad \text{O} \\
\text{2, Zn, acetic acid} & \quad \text{O} \\
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH} & \quad \text{O}
\end{align*}
\]