Alkenes

- Alkenes are hydrocarbons that contain a carbon-carbon double bond (C=C).
- Unsaturated hydrocarbons.
- Also called olefins.
- Characterized by molecular formula $C_nH_{2n}$.

Alkene IUPAC Nomenclature

- Find the longest continuous chain that includes the double bond.
- Replace the -ane ending of the unbranched alkane having the same number of carbons by -ene.
- Number the chain in the direction that gives the lowest number to the doubly bonded carbon.

1-Butene

4-Bromo-3-methyl-1-butene

- If a substituent is present, identify its position by number.
- The double bond takes precedence over alkyl groups and halogens when the chain is numbered.
Alkene IUPAC Nomenclature

2-Methyl-3-butene-1-ol

- If a substituent is present, identify its position by number.
- Hydroxyl groups take precedence over the double bond when the chain is numbered.

Cycloalkene IUPAC Nomenclature

6-Ethyl-1-methylcyclohexene

- Replace the -ane ending of the cycloalkane having the same number of carbons by -ene.
- Number through the double bond in the direction that gives the lower number to the first-appearing substituent.

Alkenyl Groups

3-Methylenehexane

4-Vinylheptane

5-Allylnonane

5-Isopropenylnonane

Structure of Ethylene

- Bond angles:
  - H–C–H = 117°.
  - H–C–C = 121°.
- Bond distances.
  - C—H = 110 pm.
  - C=C = 134 pm.
- Planar.
Physical Properties of Alkenes
(Dipole Moment)

• What is the direction of dipole moment?
• Does a methyl group donate electrons to the double bond, or does it withdraw them?

\[ \text{H}_2\text{C} = \text{C} \quad \mu = 0 \text{ D} \]

\[ \text{H}_3\text{C} = \text{C} \quad \mu = 0.3 \text{ D} \]

\[ \text{H}_2\text{C} = \text{C} \quad \mu = 0 \text{ D} \]

\[ \text{H}_3\text{C} = \text{C} \quad \mu = 0.3 \text{ D} \]

Chlorine is electronegative and attracts electrons.

\[ \text{H}_2\text{C} = \text{C} \quad \mu = 1.4 \text{ D} \]

\[ \text{H}_3\text{C} = \text{C} \quad \mu = 1.7 \text{ D} \]

\[ \text{H}_2\text{C} = \text{C} \quad \mu = 1.4 \text{ D} \]

\[ \text{H}_3\text{C} = \text{C} \quad \mu = 1.7 \text{ D} \]

\[ \text{D} = 1.4 + 0.3 = 1.7 \mu \]
Disubstituted alkenes are more stable than monosubstituted alkenes.

Methyl group donates electrons to the double bond.

Relative Stabilities of Alkenes

- Double bonds are classified according to the number of carbons attached to them.

Substituent Effects on Alkene Stability

- **Electronic:**
  - Disubstituted alkenes are more stable than monosubstituted alkenes.
  - Alkyl groups stabilize double bonds more than hydrogen.

- **Steric:**
  - *trans* alkenes are more stable than *cis* alkenes.
  - *cis* alkenes are destabilized by van der Waals strain.

Problem

- Give the structure or make a molecular model of the most stable $C_6H_{12}$ alkene.
Solution

More highly substituted double bonds are more stable than less highly substituted ones.

Substituent Effects on Alkene Stability

Electronic:
- Disubstituted alkenes are more stable than monosubstituted alkenes.
- Alkyl groups stabilize double bonds more than hydrogen.

Steric:
- trans alkenes are more stable than cis alkenes.
- cis alkenes are destabilized by van der Waals strain.

Which isomer is more stable?

van der Waals strain due to crowding of cis-methyl groups

 cis-2-butene  trans-2-butene
• Due to steric effect \textit{cis} is less stable than \textit{trans}.

\textbf{Preparation of Alkenes}

- Industrial synthesis:
  ➢ Dehydrogenation of alkanes.
- Laboratory-scale synthesis:
  ➢ Elimination reactions of:
    - Alcohols.
    - Alkyl halides.

\textbf{Dehydrogenation of Alkanes}

\[ \begin{align*}
\text{H}_3\text{C}-\text{CH}_3 & \quad \xrightarrow{750 \, ^\circ \text{C}} \quad \text{H}_2\text{C}=\text{CH}_2 + \text{H}_2 \\
\text{H}_3\text{C}-\text{CH}_2-\text{CH}_3 & \quad \xrightarrow{750 \, ^\circ \text{C}} \quad \text{H}_2\text{C}=\text{CH}-\text{CH}_3 + \text{H}_2
\end{align*} \]

- limited to industrial syntheses of ethylene, propene, 1,3-butadiene, and styrene.
- Important economically, but rarely used in laboratory-scale syntheses

\textbf{\( \beta \)-Elimination Reactions}

\[ \text{X-C-C-Y} \xrightarrow{\beta} \text{C=C} + \text{X-Y} \]

- Dehydration of alcohols:
  - (\( X = H; \ Y = \text{OH} \)).
- Dehydrohalogenation of alkyl halides:
  - (\( X = H; \ Y = \text{Br or Cl or I} \)).
**Dehydration of Alcohols**

\[ \text{H-CH}_2\text{-CH}_2\text{-OH} \xrightarrow{\text{H}_2\text{SO}_4, \text{Heat}} \text{H}_2\text{C}\text{=CH}_2 + \text{H}_2\text{O} \]

- Acid catalyzed dehydration.
- Works for both cyclic and acyclic alcohols.

**Relative Reactivity of Alcohols**

<table>
<thead>
<tr>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>Reactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>H</td>
<td>C-H</td>
<td>Tertiary &lt;br&gt;most reactive</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>C-OH</td>
<td>Secondary</td>
</tr>
<tr>
<td>H</td>
<td>R1</td>
<td>C-OH</td>
<td>Primary &lt;br&gt;least reactive</td>
</tr>
</tbody>
</table>

- Order of decreasing reactivity: \(3^\circ > 2^\circ > 1^\circ\).

**Regioselectivity of Alcohol Dehydration**

- How many products?

**Regioselectivity of Alcohol Dehydration**

- A reaction that can proceed in more than one direction, but in which one direction predominates, is said to be regioselective.
Regioselectivity of Alcohol Dehydration

\[
\text{HO} \quad \xrightleftharpoons{\text{H}_2\text{SO}_4, \text{Heat}} \quad \begin{align*}
\text{H}_2\text{C} = \text{CH}_2 + \text{H}_2\text{C} = \text{CH}_3
\end{align*}
\]

- Ratio?

\[
\text{HO} \quad \xrightleftharpoons{\text{H}_2\text{SO}_4, \text{Heat}} \quad \begin{align*}
\text{H}_2\text{C} = \text{CH}_2 + \text{H}_2\text{C} = \text{CH}_3
\end{align*}
\]

- It is a regioselective reaction (ratio = 90:10).
- Why is it so?

The Zaitsev Rule

\[
\begin{align*}
\text{R} & \xrightarrow{2 \text{Hs}} \text{R} - \text{R} - \text{C} - \text{C} - \text{CH}_2 - \text{R} \\
\text{H} & \xrightarrow{3 \text{Hs}} \text{R} - \text{R} - \text{C} - \text{C} - \text{CH}_2 - \text{R} \\
\text{CH}_3 & \xrightarrow{2 \text{Hs}} \text{R} - \text{R} - \text{C} - \text{C} = \text{CH}_2 - \text{R} + \text{H}_2\text{O}
\end{align*}
\]

- The principal alkene is the one formed by loss of H from the \(\beta\)-carbon having the fewest hydrogens.

Problem

1. \[
\begin{align*}
\text{H}_2\text{C} = \text{CH}_2 & \quad \text{major} \\
\text{C}_6\text{H}_{10} & \quad \text{minor}
\end{align*}
\]

2. \[
\begin{align*}
\text{H}_2\text{C} = \text{CH}_2 & \quad \text{minor} \\
\text{C}_6\text{H}_{10} & \quad \text{major}
\end{align*}
\]

- Which is the correct equation 1 or 2?
Solution

1. More substituted alkene is the major alkene.

2. 

Stereoselectivity of Alcohol Dehydration

- A stereoselective reaction is one in which a single starting material can yield two or more stereoisomeric products, but gives one of them in greater amounts than any other.

The Mechanism of Acid-Catalyzed Dehydration of Alcohols

- It is believed that the mechanism involves formation of carbocations intermediates.
- Thus, factors affecting carbocation’s stability would play an important role in both reactivity and regioselectivity.
- To study the mechanism, we have to fully understand:
  - Carbocations.
  - Brønsted-Lowry Acids & Bases.

Carbocations

$R_1\text{C}^{\text{+}}R_2$

$R = H$ or alkyl or aryl

- An alkyl residue in which one carbon is trivalent and carries a positive charge.
- Thus, it is electron deficient.
- Unstable.
The Structure of Carbocations

- Carbocations are trigonal planar ($sp^2$).
- Highly reactive because the positively charged carbon atom has only six electrons in its valence level, not eight (vacant $p$ orbital).

The Relative Stabilities of Carbocations

- The relative stabilities are related to the number of alkyl groups attached to the positively charged trivalent carbon atom.

- Tertiary carbocations are the most stable ($sp^2$).
- Secondary carbocations are more stable than primary carbocations ($sp^3$).
- Methyl carbocation is the least stable ($sp^3$).

The Relative Stabilities of Carbocations

- Why more substituted carbocations have greater stability?
- Because of hyperconjugation!

- The Carbocation has a vacant $p$ orbital.
- The tert-carbocation has 3 carbons with C–H bonds adjacent to the carbocation.
Each C–H bond has 2 electrons.

Electron density from one of the C–H bonds of the methyl group flows into the vacant $p$ orbital of the carbocation (hyperconjugation).

Shifting electron density in this way makes the $sp_2$-hybridized carbon of the carbocation somewhat less positive, and the hydrogens of the methyl group assume some of the positive charge.

Delocalization of the charge in this way leads to greater stability.

Tertiary carbocations have three carbons with C–H or C–C bonds adjacent to the carbocation that can overlap partially with the vacant $p$ orbital.
**The Relative Stabilities of Carbocations**

- Secondary carbocations have only two adjacent carbons with C–H or C–C bonds to overlap with the carbocation; hence, the possibility for hyperconjugation is less and the secondary carbocation is less stable.

- Primary carbocations have only one adjacent carbon from which to derive hyperconjugative stabilization, and so they are even less stable.

**Reactions of Carbocations**

- A carbocation can:
  - React with nucleophiles.
  - Lose a proton form the β–carbon to form an alkene.
  - Rearrange (less stable to more stable).

- A methyl carbocation has no possibility for hyperconjugation, and it is the least stable of all in this series.
Brønsted-Lowry Acids & Bases

\[ \begin{align*}
\text{H} - \overset{\text{\(\delta^+\)}}{\text{O}} & : + \quad \text{H} - \overset{\text{\(\delta^-\)}}{\text{Cl}} : \\
\text{H} & \quad \text{H} + \quad \overset{\text{\(\delta^-\)}}{\text{Cl}} : \\
\text{Base (proton acceptor)} & \quad \text{Acid (proton donor)} \\
\text{Conjugate acid} & \quad \text{Conjugate base}
\end{align*} \]

- According to the Brønsted-Lowry, an acid is a substance that can donate (or lose) a proton, and a base is a substance that can accept (or remove) a proton.

The Use of Curved Arrows in Reaction Mechanism

- Curved arrows are used to show the direction of electron flow in a reaction.
- The curved arrow begins with a covalent bond or unshared electron pair (a site of higher electron density) and points toward a site of electron deficiency.
- The curved arrow does not show the movement of atoms.
- The atoms are assumed to follow the flow of electrons.

The Use of Curved Arrows in Reaction Mechanism

\[ \begin{align*}
\text{H} - \overset{\text{\(\delta^+\)}}{\text{O}} & : + \quad \text{H} - \overset{\text{\(\delta^-\)}}{\text{Cl}} : \\
\text{H} & \quad \text{H} + \quad \overset{\text{\(\delta^-\)}}{\text{Cl}} :
\end{align*} \]

- A water molecule uses one of the nonbonding electron pairs to form a bond to a proton of HCl.
- The bond between the hydrogen and chlorine breaks with the electron pair going to the chlorine atom.

Mechanism of Acid-Catalyzed Dehydration of tert-Butyl Alcohol: An E1 Reaction

\[ \text{CH}_3\overset{\text{CH}}{\text{O}} \quad \text{heat} \quad \text{H}_2\text{SO}_4 \rightarrow \text{CH}_3\overset{\text{C} \equiv \text{CH}_2} {\text{H}_3} \ + \text{H}_2\text{O} \]

- E1: The elimination reaction rate depends only on one reactant which is the alcohol.
- Three steps are encountered.
An acid-base reaction, a proton is rapidly transferred from the acid to one of the unshared electron pairs of the alcohol.

In dilute H₂SO₄ the acid is hydronium ion; in concentrated H₂SO₄ the initial proton donor is H₂SO₄ itself.

An acid-base reaction, a proton is rapidly transferred from the acid to one of the unshared electron pairs of the alcohol.

This step is characteristic of all reactions of an alcohol with a strong acid.

The presence of the positive charge on the oxygen of the protonated alcohol weakens all bonds to oxygen.

The carbon–oxygen breaks heterolytically.

Slow and rate determining.
**Mechanism of Acid-Catalyzed Dehydration of Primary Alcohols: An E2 Reaction**

- **E2**: The elimination reaction rate depends on both reactants, the alcohol and the acid.
- Dehydration of primary alcohols apparently proceeds through an E2 mechanism because the primary carbocation required for dehydration by an E1 mechanism is relatively unstable.

- **The alcohol accepts a proton from the acid in a fast step.**
- **In dilute H–A the acid is hydronium ion (H₃O⁺); in concentrated H–A the initial proton donor is H–A itself.**
Mechanism of Acid-Catalyzed Dehydration of Primary Alcohols: An E2 Reaction

- A base removes a hydrogen from the $\beta$ carbon as the double bond forms and the protonated hydroxyl group departs (rate determining).
- The base may be another molecule of the alcohol or the conjugate base of the acid.

Rearrangement During Dehydration of Secondary Alcohols

- The carbon skeleton of the reactant is different from that of the products.

The Mechanism: Step 1

- Formation of the protonated alcohol.
- Proton donor is either $\mathbf{H-A}$ or $\mathbf{H_3O}^+$.

The Mechanism: Step 2

- The protonated alcohol loses water and a secondary carbocation forms.
**The Mechanism: Step 3**

- The less stable, 2° carbocation rearranges to a more stable 3° carbocation.
- Methane (CH₃⁻) migration (1,2 shift).

**The Mechanism: Step 4**

- Finally, a proton is removed from the new carbocation (by a Lewis base in the reaction mixture) and an alkene is formed.

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**Why Path (b) is more favored?**

- The Zaitsev Rule: The principal alkene is the one formed by loss of H from the β-carbon having the fewest hydrogens.

**Why Path (b) is more favored?**

- The Zaitsev Rule: The principal alkene is the one formed by loss of a proton (H⁺) from the β-carbon having the fewest hydrogens.

**Alkanide (R⁻) Migration**

- Carbocation rearrangements occur almost invariably when the migration of an alkanide ion (e.g. CH₃⁻) or hydride ion (H⁻) can lead to a more stable carbocation.
**Hydride (H⁻) Migration (or Shift)**

- Carbocation rearrangements occur almost invariably when the migration of an alkanide ion (e.g. CH₃⁻) or hydride ion (H⁻) can lead to a more stable carbocation.

**β-Elimination Reactions**

- Dehydration of alcohols:
  - (X = H; Y = OH).
- Dehydrohalogenation of alkyl halides:
  - (X = H; Y = Br or Cl or I)

**Dehydrohalogenation of Alkyl Halides**

- It is a useful method for the preparation of alkenes.
- It consumes bases.
E2 and E1 Mechanisms

- Two possible mechanisms: E2 (preferred) or E1.
- The mechanism depends on the nature of the alkyl halide and the base.

The E2 Mechanism

- Formation of the more substituted alkene is favored with a small base.

E2 and E1 Mechanisms

- Formation of the less substituted alkene is favored with a bulky base.

- It exhibits second order kinetics.
- First order in alkyl halide & first order in base.
- The rate determining step involves both alkyl halide and base (i.e. bimolecular).
The E2 Mechanism

Rate = \( k[\text{alkyl halide}][\text{base}] \)

- Rate of elimination depends on halogen weaker C–X bond.
- Faster rate: R–I > R–Br > R–Cl > R–F.
- C–X bond breaks in the rate determining step.

• C–H bond breaks.
• \( \pi \) component of double bond forms.
• C–X bond breaks.

The best reaction conditions to use when synthesizing an alkene by dehydro-halogenation are those that promote and E2 mechanism.
The Stereochemistry of E2 Reactions

• The five atoms involved in the transition state of an E2 reaction (including the base) must lie in the same plane.
• The coplanarity of the $\text{H–C–C–LG}$ unit would ensure proper overlap of orbitals to form the $\pi$ bond of the alkene.
• There are two ways that this can happen:
  o Anti coplanar transition state.
  o Syn coplanar transition state.

• The anti coplanar conformation is the preferred one.
  • the anti coplanar is more stable (staggered) than the syn coplanar (eclipsed).

The Stereochemistry of E2 Reactions

• Two groups axially oriented on adjacent carbons in a chair conformation of cyclohexane are anti coplanar.
• If one of these groups is a hydrogen and the other a leaving group, the geometric requirements for an anti coplanar E2 transition state are met.

• Which conformation can undergo elimination?
A Newman projection formula shows that the hydrogen and the chlorine are anti coplanar when they are both axial.

Elimination is possible from the conformation where the chlorine is axial (to ensure proper orbital overlap).
**The Stereochemistry of E2 Reactions**

- Elimination is possible from the conformation where the chlorine is axial (to ensure proper orbital overlap).

  The more substituted alkene is the major product (The Zaitsev Rule).

- The less substituted alkene is the major product (Why?).

  - The alkyl groups are both equatorial and the chlorine is axial (more stable conformation).
  - Two axial hydrogen atoms on both C1 and C3.

  - The base can attack either of these hydrogen atoms and achieve an anti coplanar transition state for an E2 reaction.
- Products corresponding to each of these transition state (2-menthene and 1-menthene) are formed rapidly.
- Ratio?

The more stable conformation of menthyl chloride has all three groups (including the chlorine) equatorial.

For the chlorine to become axial, menthyl chloride has to assume a conformation in which the large isopropyl group and the methyl group are also axial (flipping).
This conformation is of much higher energy, and the free energy of activation for the reaction is large because it includes the energy for the conformational change.

Hydrogen atom on C3 is axial.
Hydrogen atom on C1 is equatorial.

Menthyl chloride undergoes an E2 reaction very slowly, and the product is entirely 2-menthene (contrary to Zaitsev’s rule).

The E1 Reaction

- Reaction conditions that favor elimination by an E1 mechanism should be avoided, in general, because the results can be too variable.

- The carbocation intermediate that accompanies an E1 reaction can undergo:
  - Rearrangement of the carbon skeleton.
  - Substitution reaction.
The E1 Mechanism: *Step 1*

- The initial step is the formation of a relatively stable tert-butyl cation.
- A chlorine departs with the electron pair that bonded it to the carbon.
- It is the rate determining step.

The E1 Mechanism: *Step 2*

- A molecule of water reacts as a base and removes one of the hydrogens from the \( \beta \) carbon of the carbocation.
- At the same time an electron pair moves in to form a double bond between the \( \alpha \) and \( \beta \) carbon atoms.

Reactions of Alkenes

- Addition of:
  - Hydrogen.
  - Hydrogen halide.
  - Sulfuric acid.
  - Water.
  - Halogen.
- Oxidation & oxidative cleavages of alkenes.
Reactions of Alkenes: Addition Reactions

- A characteristic reaction of compounds with a C=C is an addition.

Catalytic Hydrogenation of Alkenes

- Alkenes react with hydrogen in the presence of a variety of metal catalysts to add one hydrogen atom to each carbon atom of the double bond.
- Uncatalyzed reaction does not take place readily at room temperature.
- The reaction produces alkanes.

Catalytic Hydrogenation of Alkenes

- Hydrogenation reactions that involve finely divided insoluble platinum, palladium, or nickel catalysts are said to proceed by heterogeneous catalysis because the substrate is soluble in the reaction mixture but the catalyst is not.
- In homogenous catalysis the catalyst is soluble in the reaction mixture.
- Typical homogenous hydrogenation catalysts include rhodium and ruthenium complexes that bear various phosphorous and other ligands.
Catalytic Hydrogenation of Alkenes

\[ R-CH=CH-R \ + \ H_2 \xrightarrow{Rh\left[\left(C_9H_6\right)P\right]_3Cl} R-CH_2-CH_2-R \ + \ \text{heat} \]

• One of the most well-known homogenous hydrogenation catalysts is Wilkinson’s catalyst, tris(triphenylphosphine)rhodium chloride.

Problem

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Khartoum, 2015

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Solution

H2, Pt

• What three alkenes yield 2-methylbutane on catalytic hydrogenation?

Solution

H2, Pt

• 2-methyl-2-butane,

• 2-methyl-2-butene, 2-methyl-1-butene,
Solution

\[ \text{H}_2, \text{Pt} \]

- 2-methyl-2-butene, 2-methyl-1-butene, and 3-methyl-1-butene.

Syn and Anti Additions

- A syn addition places the parts of the adding reagent on the same face of the reactant.
- An anti addition places the parts of the adding reagent on opposite faces of the reactant.

Alkene

Syn addition

Anti addition
**Catalytic Hydrogenation: Syn Addition**

- **Steps:**
  1. Hydrogen adsorption.
  2. Adsorption of the alkene.
  3. Stepwise transfer of both hydrogen atoms to the same face of the alkene (syn addition).

- Finally divided metal (Pt, Pd, or Ni) deposited on the surface of powdered carbon (charcoal).
Mechanism of Catalytic Hydrogenation

- Hydrogen adsorbs to the metal by a chemical reaction where unpaired electrons on the surface of the metal pair with the electrons of hydrogen & bind the hydrogen to the surface.

- The collision of an alkene with the surface bearing adsorbed hydrogen causes adsorption of the alkene as well.

- A stepwise transfer of hydrogen atoms takes place, and this produces an alkane.
Mechanism of Catalytic Hydrogenation

- The alkane product leaves the catalyst surface.

Heats of Hydrogenation

- Can be used to measure relative stability of isomeric alkenes.
- Correlation with structure is same as when heats of combustion are measured.
- The more stable an alkene is the lower will be its heat of hydrogenation.

Heats of Hydrogenation of Isomers (kJ/mol)

- Product is CH$_3$CH$_2$CH$_2$CH$_3$.

Problem

- Given three heats of hydrogenations: 126, 118, and 112 kJ/mol.
- Match each of the above alkenes with its correct heat of hydrogenation.
Solution

126 kJ/mol (monosubstituted)
118 kJ/mol (disubstituted)
112 kJ/mol (trisubstituted)

• Order of decreasing stability:
  Trisubs. > disubs. > monosubs.
• Order of decreasing heat of hydrogenation:
  monosubs. > disubs. > Trisubs.

Stereochemistry of Catalytic Hydrogenation

• Hydrogenation is a stereoselective reaction.
• The hydrogen atoms are added to less crowded face of double bond.
• A reaction in which a single starting material can give two or more stereoisomeric products but yields one of them in greater amounts than the other (or even to the exclusion of the other) is said to be stereoselective.

Both products correspond to syn addition of H₂.

But only this one is formed.
If one of the double bond carbon atoms is stereogenic, the products are enantiomeric alkanes.

In the absence of a chiral ligand the products are racemic mixture (ee = 0%).

A characteristic reaction of compounds with a C=C is an addition.
Understanding Additions to Alkenes-1

- An addition reaction results in the conversion of one π bond and one σ bond into two σ bonds (energetically favorable).

Understanding Additions to Alkenes-2

- The heat evolved in making two σ bonds exceeds that needed to break one σ bond and one π bond (usually exothermic).

- The electrons of the π bond are exposed.
- Because the π bond results from overlapping p orbitals, the π electrons lie above and below the plane of the double bond.
The electron pair of the \( \pi \) bond is distributed throughout both lobes of the \( \pi \) molecular orbital.

- The electrons of the \( \pi \) bond are exposed.
- Because the \( \pi \) bond results from overlapping \( p \) orbitals, the \( \pi \) electrons lie above and below the plane of the double bond.

Electrophilic Addition of Hydrogen Halides to Alkenes

- Electrophiles are molecules or ions that can accept an electron pair.
- Nucleophiles are molecules or ions that can furnish an electron pair (i.e., Lewis bases).
- Any reaction of an electrophile also involves a nucleophile.
- In the protonation of an alkene the electrophile is the proton donated by an acid; the nucleophile is the alkene.

- Hydrogen halides, for example, react with alkenes by donating a proton to the \( \pi \) bond.
Electrophilic Addition of Hydrogen Halides to Alkenes

- The proton uses the two electrons of the π bond to form a σ bond to one of the carbon atom.

Electrophilic Addition of Hydrogen Halides to Alkenes

- This leaves a vacant p orbital and a positive charge on the other carbon.

Electrophilic Addition of Hydrogen Halides to Alkenes

- The carbocation may then combine with the halide ion by accepting an electron pair.

Mechanism of the Reaction: Step 1

- The π electrons of the alkene form a bond with a proton from H–X to form a carbocation and a halide ion.
- Rate-determining step.
Mechanism of the Reaction: Step 2

- The halide ion reacts with the carbocation by donating an electron pair; the result is an alkyl halide.

Regioselectivity of the Addition Reaction

- When a reaction that can potentially yield two or more constitutional isomers actually produces only one (or a predominance of one), the reaction is said to be regioselective.

Regioselectivity of the Addition Reaction

- The addition of $\text{H--X}$ to an unsymmetrical alkene could conceivably occur in two ways.
- One product usually predominates.

- The addition of $\text{H--Br}$ to propene could conceivably lead to either 1-bromopropane or 2-bromopropane.
- The major product is 2-bromopropane.
Regioselectivity of the Addition Reaction

When 2-methylpropene reacts with H–Br, the major product is 2-bromo-2-methylpropane, not 1-bromo-2-methylpropane.

The chief product of the reaction is 2-bromopropane because the more stable secondary carbocation is formed preferentially in the first step.

Markovnikov’s Rule

In the addition of H–Br to an alkene, the hydrogen atoms adds to the carbon atom of the double bond that already has the greater number of hydrogen atoms.

The chief product of the reaction is 2-bromopropane because the more stable secondary carbocation is formed preferentially in the first step.
• The chief product of the reaction is 2-bromo-2-methylpropane because the more stable tertiary carbocation is formed preferentially in the first step.

Rearrangement in Addition Reactions

• Because carbocations are formed in the addition of H–X to an alkene, rearrangements invariably occur when the carbocation initially formed can rearrange to a more stable one.

Assignment

• Provide mechanistic explanations for the following observations:
  a) The addition of hydrogen chloride to 3-methyl-1-butene produces two products: 2-chloro-3-methylbutane and 2-chloro-2-methylbutane.
  a) The addition of hydrogen chloride to 3,3-dimethyl-1-butene produces two products: 3-chloro-2,2-dimethylbutane and 2-chloro-2,3-dimethylbutane.

Radical Additions to Alkenes: The Anti-Markovnikov Addition of HBr

• When alkenes are treated with HBr in the presence of peroxides, the hydrogen atom becomes attached to the carbon atom with the fewer hydrogen atoms (anti-Markovnikov addition).
  • HF, HCl, and HI do not give anti-Markovnikov addition even when peroxides are present.
A Radical Mechanism for The Reaction

\[
\begin{align*}
\text{Step 1:} & \quad \text{Heat brings about homolytic cleavage of the weak oxygen-oxygen bond.} \\
\end{align*}
\]

\[
\begin{align*}
\text{Step 2:} & \quad \text{The alkoxy radical abstract a hydrogen atom from HBr, producing a bromine atom.} \\
\end{align*}
\]

\[
\begin{align*}
\text{Step 3:} & \quad \text{A bromine atom adds to the double bond to produce the more stable 2° radical.} \\
\end{align*}
\]
A Radical Mechanism for The Reaction

\[
\begin{align*}
\text{Br-CH}_2\text{-CH-CH}_2 + H\text{-Br} & \rightarrow \text{Br-CH}_2\text{-CH-CH}_2 + \text{Br} \\
\end{align*}
\]

• **Step 4**: The 2° radical abstracts a hydrogen atom from HBr. This leads to the product and regenerates a bromine atom.

The repetition of steps 3 and 4 lead to a chain reaction.

Markovnikov Addition of HBr to Alkenes

**Ionic Addition**

\[
\begin{align*}
\text{H}_2\text{C=CH-CH}_3 + \text{H-Br} & \rightarrow \text{CH}_3\text{-CH-CH}_3 + \text{Br} \\
\end{align*}
\]

• In the absence of peroxides, the reagent that attacks the double bond first is a proton. It attaches itself to a carbon by an ionic mechanism so as to form the more stable carbocation.

Anti-Markovnikov Addition of HBr to Alkenes

**Radical Addition**

\[
\begin{align*}
\text{H}_2\text{C=CH-CH}_3 + \text{Br} & \rightarrow \text{CH}_3\text{-CH-CH}_2\text{Br} + \text{Br} \\
\end{align*}
\]

• In the presence of peroxides, the reagent that attacks the double bond first is the larger bromine atom. It attaches itself to the less hindered carbon atom by a radical mechanism so as to form the more stable radical intermediate.
Stereochemistry of the Ionic Addition to an Alkene

\[ \text{CH}_3\text{CH}_2\text{CH}≡\text{CH}_2 + \text{HX} \rightarrow \text{CH}_3\text{CH}_2\text{CHCH}_3^* \]

- Addition of HX to 1-butene leads to the formation of a product, 2-halobutane, which contains a chiral center.
- The product, therefore, can exist as a pair of enantiomers.
- Is one enantiomer formed in greater amount than the other.

Addition of Sulfuric Acid to Alkenes

- Alkyl hydrogen sulfates are produced when alkenes are treated with cold concentrated sulfuric acid.

The Stereochemistry of the Reaction

- The carbocation, being planar, reacts with the halide ion at equal rates by path (a) or (b) to form the enantiomers as a racemate.

Addition of Sulfuric Acid to Alkenes

- The addition of sulfuric acid is regioselective, and it follows Markovnikov’s rule.
- Propene reacts to yield isopropyl hydrogen sulfate rather than propyl hydrogen sulfate.
Addition of Water to Alkenes: Acid-Catalyzed Hydration

- Preparation of low-molecular-weight alcohols.
- The acids most commonly used are dilute aqueous solutions of H₂SO₄ and H₃PO₄.
- It follows Markovnikov’s rule (regioselective).

Mechanism: Step 1

- The alkene donates an electron pair to a proton to form the more stable 3° carbocation.
- Rate determining step.
**Mechanism: Step 2**

\[
\begin{align*}
\text{H}_3\text{C}-\text{C}^+\text{CH}_3 + \text{H}_2\text{O} & \quad \text{fast} \quad \text{H}_3\text{C}-\text{C}^+\text{O}^-\text{H} \\
\end{align*}
\]

- The 3° carbocation reacts with a molecule of water to form a protonated alcohol.

**Mechanism: Step 3**

\[
\begin{align*}
\text{H}_3\text{C}-\text{C}^+\text{O}^-\text{H} + \text{H}_2\text{O} & \quad \text{fast} \quad \text{H}_3\text{C}-\text{O}^-\text{H} + \text{H}_2\text{O} \\
\end{align*}
\]

- A transfer of a proton to a molecule of water leads to the product.

**Rearrangements in Acid-Catalyzed Hydration of Alkenes**

\[
\begin{align*}
\text{CH}_3\text{CH}=&\text{CH}_2 + \text{H}_2\text{SO}_4 & \quad \text{H}_2\text{O} \\
\text{HO-CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 & \quad \text{major product} \\
\end{align*}
\]

- Because the reaction involves the formation of a carbocation in the first step, the carbocation formed initially invariably rearranges to a more stable one if such a rearrangement is possible.

**Assignment**

- Outline all steps in a mechanism showing how 2,3-dimethyl-2-butanol is formed in the acid-catalyzed hydration of 3,3-dimethyl-1-butene.
- Hint: initially formed carbocation rearranges to give a more stable one.
Oxymercuration-Demercuration: Markovnikov Addition

- A useful two-steps method for preparation of alcohols from alkenes.
- Highly regioselective.
- It follows Markovnikov’s rule.
- Rearrangements seldom occur in this method.

Step 1: Oxymercuration

\[
\text{CH}_2=\text{CH} + \text{H}_2\text{O} + \text{Hg}(\text{O}-\text{C}-\text{CH}_3)_2 \rightarrow \text{HgO-CH}_2\text{CH}_3 + \text{H}_2\text{O} + \text{CH}_2=\text{CH}_2
\]

- Alkenes react with mercuric acetate in a mixture of tetrahydrofuran (THF) and water to produce (hydroxylalkyl)mercury compounds.

Step 2: Demercuration

\[
\text{CH}_2=\text{CH} + \text{OH}^- + \text{NaBH}_4 \rightarrow \text{CH}_2=\text{CH} + \text{Hg} + \text{H}_3\text{C}-\text{C}-\text{O}^-\]

- These (hydroxylalkyl)mercury compounds can be reduced to alcohols with sodium borohydride.

Regioselectivity of Oxymercuration-Demercuration

- The net orientation of the addition of the elements of water, H– and –OH, is in accordance with Markovnikov’s rule.
- The H– becomes attached to the carbon atom of the double bond with greater number of hydrogen atoms.
Complete the above reaction.
Assignment

\[
\begin{align*}
\text{CH}_3 & \quad \text{Hg(OAc)}_2 \\
\text{H}_2\text{C} \equiv \text{C} \equiv \text{CH} = \text{CH}_2 & \quad \text{THF/H}_2\text{O} \\
\text{CH}_3 & \quad \text{Hg(OAc)}_2
\end{align*}
\]

- Draw a mechanism for oxymercuration.
- Hint:
  \[
  \text{Hg(OAc)}_2 \xrightarrow{\oplus} \text{HgOAc} + \text{OAc}
  \]

Hydroboration-Oxidation: Anti-Markovnikov Syn Hydration

- Hydration of a double bond in an anti-Markovnikov sense can be achieved through the use of diborane (\(\text{B}_2\text{H}_6\)).
- The addition of water is indirect, and two reactions are involved:
  - Hydroboration.
  - Oxidation.

Hydroboration-Oxidation: Anti-Markovnikov Syn Hydration

- Hydroboration: addition of a boron atom and hydrogen atom to the double bond.
- Oxidation: oxidation and hydrolysis of the alkylborane intermediate to an alcohol.

Hydroboration-Oxidation: Anti-Markovnikov Syn Hydration

- Hydroboration-oxidation takes place with syn stereochemistry, as well as anti-Markovnikov regiochemistry.
- No rearrangement.
Rational for Regioselectivity

- Steric factor: In each step the bulky boron-containing group becomes attached to the less substituted carbon atom of the double bond.
- Electronic factor (see the mechanism).

Mechanism of Hydroboration

- Initial formation of a π complex.
- Electrons shift in the direction of the boron atom and away from the more substituted carbon atom of the double bond.
- This results in a cyclic four-atom transition state.
Mechanism of Hydroboration

- The dashed bonds in the transition state represent bonds that are partially formed or partially broken.

- The transition state results in syn addition of the hydrogen and boron group.

- The boron adds to the less hindered carbon.

- The more substituted carbon atom develops a partial positive charge ($\delta^+$).
Mechanism of Hydroboration

\[ \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} + \text{H} \cdots \text{B} \cdots \text{H} \rightarrow \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \rightarrow \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \]

\( \pi \text{Complex} \)

\[ \left[ \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \right] \rightarrow \left[ \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \right] \]

\( \delta^+ \text{carbon atom (regioselectivity).} \)

- The electron-releasing alkyl groups stabilize the (\( \delta^+ \)) carbon atom (regioselectivity).

- Thus, both electronic and steric factors account for the anti-Markovnikov orientation of the addition.

Mechanism of Hydroboration

\[ \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} + \text{H} \cdots \text{B} \cdots \text{H} \rightarrow \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \rightarrow \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \]

\( \pi \text{Complex} \)

\[ \left[ \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \right] \rightarrow \left[ \text{H}_3\text{C} \cdots \text{C} \cdots \text{C} \cdots \text{H} \right] \]

\( \delta^+ \text{carbon atom (regioselectivity).} \)

- Finally, an alkylborane is generated.

- The other B–H bonds of the alkylborane can undergo similar additions, leading finally to a trialkyborane.
Oxidation and Hydrolysis of Alkylboranes

\[
\begin{align*}
R - B - R & \xrightarrow{\text{H}_2\text{O}_2, \text{aq. NaOH}} 3R-\text{OH} + \text{B(ONa)}_3 \\
25^\circ \text{C} & 
\end{align*}
\]

• The oxidation and hydrolysis are effected by the addition of hydrogen peroxide in an aqueous base.

Oxidation and Hydrolysis of Alkylboranes

- The oxidation and hydrolysis steps take place with retention of configuration at the carbon initially bearing boron and ultimately bearing the hydroxyl group.
Oxidation and Hydrolysis of Alkylboranes

\[ \text{H-O-O-H} \xrightarrow{\text{NaOH}} \]

\[ \text{R-B-O-R} + \text{O-O-H} \xrightarrow{\text{Trialkylborane, Hydroperoxide ion}} \]

\[ \text{R-B-O-O-H} \xrightarrow{\text{Unstable intermediate}} \]

\[ \text{R-O} \xrightarrow{\text{Repeat sequence twice}} \text{B-O-R} \xrightarrow{\text{Borate ester}} \]

Oxidation and Hydrolysis of Alkylboranes

\[ \text{R-O} \xrightarrow{\text{Trialkylborate ester}} \text{R-O-B-O-R} \xrightarrow{\text{H-O-R}} \]

\[ \text{R-O-B-O-H} \xrightarrow{\text{Alcohol}} \]

\[ \text{R-O} + \text{H-O-R} \xrightarrow{\text{Alcohol}} \text{R-O-B-O-R} \]
Oxidation and Hydrolysis of Alkylboranes

• Alkylborane oxidation begins with addition of a hydroperoxide anion (HOO⁻) to the trivalent boron atom.

• An unstable intermediate is formed that has a formal negative charge on the boron.

• Migration of an alkyl group with a pair of electrons from the boron to the adjacent oxygen leads to neutralization of the charge on boron and displacement of a hydroxide anion.
Oxidation and Hydrolysis of Alkylboranes

- Repetition of the hydroperoxide anion addition and migration steps occurs twice more until all of the alkyl groups have become attached to oxygen atoms, resulting in a trialkyl borate ester, B(OR)₃.

- The borate ester then undergoes basic hydrolysis to produce three molecules of the alcohol and an inorganic borate anion.
Problem

- Complete the above scheme by giving the best condition for each synthesis.

Solution

- Acid-catalyzed hydration yields 2-hexanol.
- Hydroboration-oxidation yields 1-hexanol.

Electrophilic Addition of Bromine and Chlorine to Alkenes

- Alkenes react rapidly with chlorine and bromine in nonnucleophilic solvents to form vicinal dihalides.
Bromine Test

- Br₂ can serve as a test for the presence of carbon–carbon multiple bonds.
- If Br₂ is added to an alkene (or alkyne), the red-brown color of Br₂ disappears almost instantly as long as the alkene (or alkyne) is present in excess.

\[
\begin{align*}
\text{C} &= \text{C} \\
\text{Br}_2 &\xrightarrow{\text{rt, dark}} \text{C} - \text{C} - \text{Br} \\
\text{Colorless} &\rightarrow \text{Red-brown} \\
\end{align*}
\]

- Rapid decolorization of Br₂/CCl₄ is a positive test for alkenes and alkynes.

Bromine Test

\[
\begin{align*}
\text{R} &\rightarrow \text{H} + \text{Br}_2 &\xrightarrow{\text{rt, dark}} &\text{No reaction} \\
\text{Alkane} &\quad \text{(colorless)} &\quad \text{Br}_2 &\quad \text{(red-brown)} \\
\end{align*}
\]

- Alkanes do not react appreciably with Br₂ or Cl₂ at room temperature and in the absence of light.
Mechanism of Halogen Addition: Step 1

- As bromine molecule approaches an alkene, the electron density of the alkene π bond repels electron density in the closer bromine, polarizing the bromine molecule and making the closer bromine atom electrophilic.

- Formation of bromonium ion.

- Br₂ is not polar, but it is polarizable.
- Electrons flow from alkene towards Br₂.

- The alkene donates a pair of electrons to the closer bromine, causing displacement of the distant bromine atom.

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• The newly bonded bromine atom donates an electron pair to the newly formed carbocation leading to formation of a bromonium ion.

Mechanism of Halogen Addition: Step 2

• Nucleophilic attack on bromonium ion by bromide ion causes the ring to open.
• Attack of bromide from side opposite C—Br bond of bromonium ion gives anti addition

Stereochemistry of the Addition of Halogens to Alkenes (e.g. Cyclopentene)

• When cyclopentene reacts with bromine in carbon tetrachloride, anti addition occurs.
• The products of the reaction are (±)-trans-1,2-dibromocyclopentane (racemate).
Stereochemistry of the Addition of Halogens to Alkenes (e.g. Cyclopentene)

- Formation of a bromonium ion in the first step.
- In the second step, a bromide ion attacks a carbon atom of the ring from the side opposite that of the bromonium ion.
- Nucleophilic attack by the bromide ion causes inversion of the configuration of the carbon being attacked.

- Ring opening is an $S_N2$ reaction.

Cyclopentene + $\text{Br}_2$

Bromonium ion
Bromide ion attacks the bromonium ion from side opposite carbon–bromine bond.

trans-Stereochemistry in vicinal dibromide

Stereochemistry of the Addition of Halogens to Cyclohexene

- When cyclohexene undergoes addition, the initial product is diaxial (proper orbital overlapping).
- The diaxial conformer rapidly converts to the diequatorial one (more stable).
- When equilibrium is reached the diequatorial form predominates.
Stereospecific Reactions

- A reaction is stereospecific when a particular stereoisomeric form of the starting material reacts in such a way that it gives a specific stereoisomeric form of the product.
- For example, the reactions of cis- and trans-2-butene with bromine are stereospecific.

Mechanism: Step 1

- This step is the same as for halogen addition to an alkene.

Halohydrin Formation

- When the halogenation of an alkene is carried out in aqueous solution, rather than a non-nucleophilic solvent, the major product is a halohydrin instead of a vic-dihalide.
Mechanism: Step 2

- A water molecule acts as the predominant nucleophile (because it is the solvent) and attacks a carbon of the ring, causing the formation of a protonated halohydrin.

Mechanism: Step 3

- The protonated halohydrin loses a proton (it is transferred to a molecule of water). This step produces the halohydrin and hydronium ion.

Regioselectivity

- If the alkene is unsymmetrical, the halogen ends up on the carbon atom with greater number of hydrogen atoms (Markovnikov’s rule).
- The more highly substituted carbon atom bears the greater positive charge because it resembles the more stable carbocation.
- Consequently, water attacks this carbon atom preferentially.

Example

\[
\begin{align*}
\text{H}_3\text{C} & \quad \text{Br}_2 \\
\text{C} &= \text{CH}_2 & \quad \text{C} &= \text{CH}_2 \\
\text{H}_3\text{C} & \quad \text{CH}_3 & \quad \text{H}_3\text{C} & \quad \text{CH}_2 \text{Br} \\
\text{CH}_3 & \quad \text{Br} & \quad \text{OH} & \quad \text{OH}_2 \\
\text{H}_3\text{C} & \quad \text{CH}_2 \text{Br} & \quad \text{CH}_3 & \quad \text{H}_3\text{O} \\
\end{align*}
\]

(73%)
Assignment

\[
\begin{align*}
\text{H}_2\text{C} & = \text{CH}_2 \\
\text{H}_2\text{C} & \quad \text{Br} \\
\text{H} & \quad \text{C} \\
& \quad \text{CH}_2 \\
\text{H} & \quad \text{Br} \\
\text{H} & \quad \text{C} \\
& \quad \text{CH}_2 \\
\text{H} & \quad \text{Br}
\end{align*}
\]

\[
\begin{align*}
\text{H}_2\text{C} & = \text{CH}_2 \\
\text{H} & \quad \text{C} \\
& \quad \text{CH}_2 \\
\text{H} & \quad \text{OH} \\
\text{H} & \quad \text{C} \\
& \quad \text{OH}
\end{align*}
\]

- Write mechanisms showing how each product is formed.

Reactions of Alkenes: Oxidation

- Alkenes undergo a number of reactions in which the carbon–carbon double bond is oxidized, e.g.:
  - Syn 1,2-Dihydroxylation.
  - Oxidative cleavage.
  - Epoxidation.
  - Anti 1,2-Dihydroxylation via epoxidation.

Syn 1,2-Dihydroxylation

- **Osmium tetroxide:**

  \[
  \begin{align*}
  \text{H}_3\text{C} & \quad \text{C} \quad \text{CH} \\
  \text{H}_3\text{C} & \quad \text{C} \\
  \text{H}_3\text{C} & \quad \text{CH} \\
  \text{H}_3\text{C} & \quad \text{CH} \\
  \text{H}_3\text{C} & \quad \text{C} \\
  \text{H}_3\text{C} & \quad \text{CH} \\
  \text{H}_3\text{C} & \quad \text{C} \\
  \text{H}_3\text{C} & \quad \text{CH}
  \end{align*}
  \]

- **Cold basic Potassium permanganate:**

Mechanism for Syn Dihydroxylation

- The mechanism involves a cyclic intermediate that results in syn addition of the oxygen atoms.
Mechanism for Syn Dihydroxylation

- Cleavage at the oxygen–metal bonds takes place without altering the stereochemistry of the two new C–O bonds.

Example

- The syn stereochemistry of this dihydroxylation can readily be observed by the reaction of cyclopentene with OsO₄.

Oxidative Cleavage

- **Ozone:**
  - cis or trans
  - \( \text{O}_3, \text{CH}_2\text{Cl}_2, -78^\circ\text{C} \)
  - \( \text{Zn/\text{HOAc}} \)

- **Hot basic Potassium permanganate:**
  - cis or trans
  - \( \text{KMnO}_4, \text{OH, H}_2\text{O} \) → heat

Cleavage with Ozone: Ozonolysis

- **2-Methyl-2-butene:**
  - \( \text{O}_3, \text{CH}_2\text{Cl}_2, -78^\circ\text{C} \)
  - \( \text{Zn/\text{HOAc}} \)

- **3-Methyl-1-butene:**
  - \( \text{O}_3, \text{CH}_2\text{Cl}_2, -78^\circ\text{C} \)
  - \( \text{Zn/\text{HOAc}} \)

- Ozonolysis has both synthetic and analytical applications.
Mechanism of Ozonolysis

- Ozone adds to the alkene to form an initial ozonide.
- The initial ozonide dissociates into reactive fragments.

- The fragments recombine to form the ozonide.
- The ozonide is then hydrolyzed to give the final ozonolysis products.

Problem

\[ C_7H_{12} \rightarrow (1) O_3, \text{CH}_2\text{Cl}_2, -78^\circ C \rightarrow \text{C} = \text{C} = \text{O} + \text{C} = \text{O} \]

- An unknown alkene with the formula \( C_7H_{12} \) undergoes ozonolysis to yield only the above product. What was the structure of this alkene?

Solution

\[ \text{1-Methylcyclohexene} \rightarrow (1) O_3, \text{CH}_2\text{Cl}_2, -78^\circ C \rightarrow \text{C} = \text{C} = \text{O} + \text{C} = \text{O} \]

- The reactant has a double bond contained in a ring.
Assignment

(a) \( \text{H}_3\text{C} = \text{C} \backslash \text{CH}_3 \) and \( \text{H}_3\text{C} - \text{C} - \text{H} \)

(b) \( \text{C}_2\text{H}_5 \) only 2 moles is produced from 1 mole of alkene

(c) \( \bigcirc \) and \( \text{H} - \text{H} \)

- Write the structures of the alkenes that would produce the above products when treated with ozone and then zinc and acetic acid.

Cleavage with Hot Basic KMnO₄

- Treatment with hot basic KMnO₄ oxidatively cleaves the double bond of an alkene.
- Alkenes with monosubstituted carbon atoms are oxidatively cleaved to salts of carboxylic acids.
- Disubstituted alkene carbons are oxidatively cleaved to ketones.
- Unsubstituted alkene carbons are oxidized to carbon dioxide.
Problem

\[ \text{C}_8\text{H}_{16} \xrightarrow{(1) \text{K}_2\text{MnO}_4, \text{OH}, \text{H}_2\text{O}, \text{heat}} \xrightarrow{(2) \text{H}_2\text{O}} \text{OH} + \text{HO} \]

An unknown alkene with the formula \( \text{C}_8\text{H}_{16} \) was found, on oxidation with hot basic permanganate, to yield the above acids. What was the structure of this alkene?

Solution

either cis- or trans-3-octene

\[ \xrightarrow{(1) \text{K}_2\text{MnO}_4, \text{OH}, \text{H}_2\text{O}, \text{heat}} \xrightarrow{(2) \text{H}_2\text{O}} \text{OH} + \text{HO} \]

The unknown alkene must have been cis- or trans-3-octene.

Epoxidation of alkenes

\[ \text{RHC} = \text{CHR} + \text{R}_1\text{C}=\text{O} - \text{O} - \text{OH} \xrightarrow{\text{epoxidation}} \text{RHC} = \text{CHR} + \text{R}_1\text{C}=\text{O} \]

Epoxides are cyclic ethers with three-membered rings.

The most widely used methods for their synthesis is the reaction of an alkene with an organic peroxy acid (epoxidation).

Stereochemistry of Epoxidation

\[ \text{C} = \text{C} \xrightarrow{\text{syn addition}} \text{C} = \text{C} \]

The addition of oxygen to the double bond is, of necessity, a syn addition.
Example

\[
\text{Peroxy acid} \quad \text{Ethanol} \\
\xrightarrow{\text{1,2-Epoxycyclohexane}} \\
(\text{cyclohexene oxide}) \\
(85\%)
\]

Mechanism of Epoxidation
Epoxide Ring Opening

- The highly strained three-membered ring in molecules of epoxides makes them much more reactive toward nucleophilic substitution.
- Ring opening is a typical reaction of epoxides and can be:
  - Acid-catalyzed (weak nucleophiles).
  - Base-catalyzed (strong nucleophiles).

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Acid-Catalyzed Ring Opening

- The acid reacts with the epoxide to produce a protonated epoxide.

\[
\text{C} = \text{C} + \text{H} - \overset{\text{O}}{\text{O}} - \overset{\text{H}}{\text{H}} \rightarrow \text{C} = \text{C} + \overset{\text{O}}{\cdot} - \overset{\text{O}}{\text{H}}
\]

- Protonated epoxide

- Weak nucleophile

- Protonated 1,2-diol

- 1,2-diol

Acid-Catalyzed Ring Opening

- The protonated epoxide reacts with the weak nucleophile (water) to form a protonated 1,2-diol.

\[
\text{H} - \overset{\text{O}}{\text{O}} - \overset{\text{H}}{\text{H}} \rightarrow \text{H} - \overset{\text{O}}{\cdot} - \overset{\text{O}}{\text{H}}
\]

- Protonated 1,2-diol

- 1,2-diol

- Protonated 1,2-diol transfers a proton to a molecule of water to form the 1,2-diol and a hydronium ion.
Example

\[ \text{CH}_3\text{OH} + \text{H}_3\text{C}-\text{C}^\ominus \text{CH}_2 \xrightarrow{\text{HA}} \text{H}_3\text{C}-\text{C}^\ominus \text{CH}_2\text{OH} \]

• Nucleophile attacks more substituted 3° carbon atom (a typical S_N1 reaction).
• 3° carbon atom bears a greater (δ+).

Example

\[ \text{CH}_3\text{OH} + \text{H}_3\text{C}^\ominus \text{C}^\ominus \text{CH}_2 \xrightarrow{} \text{H}_3\text{C}-\text{C}^\ominus \text{CH}_2\text{OH} \]

• Nucleophile attacks more substituted 3° carbon atom (a typical S_N1 reaction).
• 3° carbon atom bears a greater (δ+).

Base-Catalyzed Ring Opening

\[ \text{R}^\ominus + \text{C}^\ominus \text{C}^\ominus \text{C}^\ominus \text{C}^\ominus \xrightarrow{\text{H}^\ominus \text{OR}} \text{R}^\ominus \text{C}^\ominus \text{C}^\ominus \text{C}^\ominus \text{R}^\ominus \]

• A strong nucleophile such as an alkoxide ion or a hydroxide ion is able to open the strained epoxide ring in a direct S_N2 reaction.

Example

\[ \text{CH}_3\text{CH}_2^\ominus \text{O}^\ominus + \text{H}^\ominus \text{C}^\ominus \text{C}^\ominus \text{C}^\ominus \text{CH}_3 \xrightarrow{\text{EtOH} \text{EtO}^\ominus} \text{CH}_3\text{CH}_2\text{O}^\ominus \text{C}^\ominus \text{C}^\ominus \text{CH}_3 \]

• Nucleophile attacks less sterically hindered 1° carbon atom (a typical S_N2 reaction).
Anti 1,2-Dihydroxylation of Alkenes via Epoxides

Epoxidation followed by acid-catalyzed hydrolysis gives us a method for anti 1,2-dihydroxylation of a double bond.

Assignment

Starting from cyclohexene show how you can prepare trans-1,2-cyclohexanediol and cis-1,2-cyclohexanediol.

Conjugated Unsaturated Systems

Species that have a $p$ orbital on an atom adjacent to a double bond are said to be conjugated unsaturated systems.

The $p$ orbital may be:

- One that contains a single electron as in the allyl radical.
- A vacant $p$ orbital as in the allyl cation.
- The $p$ orbital of another double bond as in 1,3-butadiene.
Allylic Substitution and the Allyl Radical

\[ \text{H}_2\text{C}==\text{CH}==\text{CH}_3 + \text{X}_2 \xrightarrow{\text{low temperature}} \text{H}_2\text{C}==\text{CH}==\text{CH}_3 \]

\[ \text{H}_2\text{C}==\text{CH}==\text{CH}_3 + \text{X}_2 \xrightarrow{\text{high temperature}} \text{H}_2\text{C}==\text{CH}==\text{CH}_2\text{X} + \text{HX} \]

- Based on the reaction conditions, propene undergoes either addition or substitution reaction when treated with Br\(_2\) or Cl\(_2\).

Radical Mechanism of Allylic Substitution

\[ \text{H}_2\text{C}==\text{CH}==\text{CH}_3 + \text{Cl}_2 \xrightarrow{400^\circ \text{C}} \text{H}_2\text{C}==\text{CH}==\text{CH}_2\text{Cl} + \text{HCl} \]

- The mechanism for allylic substitution is the same as the chain mechanism for alkane halogeneation.

- In allylic substitution a halogen atom replaces one of the hydrogen atoms of the methyl group of propene.
- These hydrogen atoms are called the allylic hydrogen atoms.
Rational for Chemoselectivity in Formation of an Allyl Radical

- The allylic carbon–hydrogen bond of propene is broken with greater ease than that of the vinylic carbon–hydrogen bond.

The Stability of the Allyl Radical

- Allylic free radicals are stabilized by electron delocalization.
- The unpaired electron of the allyl radical and the two electrons of the π bond are delocalized over all three carbon atoms.
Relative Stability of Allyl Radical

<table>
<thead>
<tr>
<th>Allylic Radicals</th>
<th>Relative Stability (kJ mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂C=CH⋅CH₂-H</td>
<td>DHP = 369 kJ mol⁻¹</td>
</tr>
<tr>
<td>(CH₃)₂C-H</td>
<td>DHP = 400 kJ mol⁻¹</td>
</tr>
<tr>
<td>(CH₃)₂CH-H</td>
<td>DHP = 413 kJ mol⁻¹</td>
</tr>
<tr>
<td>H₃C⋅CH₂CH₂-H</td>
<td>DHP = 423 kJ mol⁻¹</td>
</tr>
<tr>
<td>H₂C=CH-H</td>
<td>DHP = 465 kJ mol⁻¹</td>
</tr>
</tbody>
</table>

- According to bond dissociation energies the relative stability is:
  Allylic > 3° > 2° > 1° > vinlylic

Mechanism

- The reaction is initiated by the formation of a small amount of bromine atom (radical).
- The main propagation steps are the same as for allylic substitution.
- NBS is nearly insoluble in CCl₄ (non polar) and provides a constant but very low concentration of Br₂ in the reaction mixture.
- Very little bromine adds to the double bond; it reacts by substitution and replaces an allylic hydrogen atom instead.

**Allylic Bromination with N-Bromosuccinimide (Low Conc. of Br₂)**

- Propene undergoes allylic bromination when it is treated with N-bromosuccinimide (NBS) in CCl₄ in the presence of peroxide or light.
Assignment

- Propose, with aid of chemical equations, a synthetic route for 3-bromocyclohex-1-ene.
- Hint: use cyclohexanol as a starting material.

Allylic Cations

- An unusually stable carbocation.

Resonance in Allylic Cations

- Delocalization of electrons in the double bond stabilizes the carbocation.
Relative Stability of Allylic Carbocation

Substituted allylic > Tertiary > Allylic > Secondary > Primary > Vinyl

- Allylic carbocations are more stable than other carbocations.

Conjugated Alkadienes

H₂C≡C≡CH₂
A cumulated diene

H₂C≡CH-CH≡CH₂
A conjugated diene

H₂C≡CH-CH₂-CH=CH₂
An isolated diene

The Stability of Conjugated Dienes

ΔH° = -254 kJ mol⁻¹
ΔH° = -239 kJ mol⁻¹

• Heats of hydrogenation of 2 mol of 1-butene and 1 mol of 1,3-butadiene.

• 1,3-Butadiene is more stable, by 15 kJ mol⁻¹, than expected.
• The conjugation imparts some extra stability to the conjugated system.
• Conjugated dienes are more stable than nonconjugated dienes.
The Stability of Conjugated Dienes

- Resonance increases stability of conjugated dienes.

Electrophilic attack on Conjugated Dienes: 1,4-Addition

Mechanism: Step 1
Mechanism: Step 2

Assignment

- Give the products of the following reactions:
  a) 2,4-Hexadiene + HCl.
  b) 1,3-Pentadiene + HCl.
- Assign each product as either major or minor.

Kinetic Control versus Thermodynamic Control of a Chemical Reaction

- In reaction of HBr with 1,3-butadiene:
  - 1,2 addition favors low temperature.
  - 1,4 addition favors high temperature.

Assignment

- Draw a possible mechanism for the above reaction.
• The energy barrier for attack of bromide ion on the allylic cation to form the 1,2-addition product is less than that to form the 1,4-addition product ($\Delta G_{1,2} < \Delta G_{1,4}$).

• At the lower temperature, the relative amounts of the products of the addition are determined by the relative rates at which the two additions occur.

• 1,2 Addition occurs faster (lower $\Delta G$) so the 1,2-addition product is the major product (kinetically favored).

• At the higher temperature, the relative amounts of the products are determined by the position of an equilibrium.
• The 1,4-addition product is the more stable, so it is the major product (thermodynamically favored).

Assignment

\[ \text{?} \]

- What is the major product of the above kinetically controlled reaction?
The Diels-Alder Reaction: A 1,4-Cycloaddition Reaction of Dienes

\[
\text{1,3-Butadiene (diene)} \quad \text{Maleic anhydride (dienophile)} \quad \text{Diels-Alder Adduct (100\%)}
\]

React at 200°C sealed tube

\[
\text{benzene} \rightarrow \text{(20\%)}
\]