Organic Chemistry

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Alkenes II

Chapter 6
6 Characteristic Reactions

Hydrochlorination (hydrohalogenation)

\[
\text{C} = \text{C} + \text{HCl} \rightarrow \text{C} - \text{C} - \text{H} - \text{Cl}
\]

Hydration

\[
\text{C} = \text{C} + \text{H}_2\text{O} \rightarrow \text{C} - \text{C} - \text{H} - \text{OH}
\]
6 Characteristic Reactions

Bromination (halogenation)

\[
\text{C} = \text{C} + \text{Br}_2 \rightarrow \text{C} \quad \text{Br} \quad \text{Br}
\]

Hydroboration

\[
\text{C} = \text{C} + \text{BH}_3 \rightarrow \text{C} \quad \text{C} \quad \text{H} \quad \text{BH}_2
\]
6 Characteristic Reactions

Hydroxylation (oxidation)

\[ \text{C}=\text{C} \quad + \quad \text{OsO}_4 \quad \rightarrow \quad \text{C} \quad \text{C} \quad \text{OH} \quad \text{OH} \]

Hydrogenation (reduction)

\[ \text{C}=\text{C} \quad + \quad \text{H}_2 \quad \rightarrow \quad \text{C} \quad \text{C} \quad \text{H} \quad \text{H} \]
A reaction mechanism describes details of how a reaction occurs:

- which bonds are broken and which new ones are formed
- the order in which bond-breaking and bond-forming steps take place
- the role of the solvent (if any)
- the role of the catalyst (if any)
- the energy of the entire system during the reaction
Potential energy (PE) diagram: a graph showing the changes in energy that occur during a chemical reaction.

Reaction coordinate: a measure of the change in position of atoms during a reaction.
6 PE Diagrams

- Heat of reaction: the difference in energy between reactants and products
  - exothermic: products are lower in energy than reactants; heat is released
  - endothermic: products are higher in energy than reactants; heat is absorbed

- Transition state: an energy maximum on a PE diagram
  - represents an unstable species of maximum PE formed during the course of a reaction
Activation Energy (Eₐ): the difference in potential energy between reactants and the transition state

- determines rate of reaction
- if activation energy is large, only a few molecular collisions occur with sufficient energy to reach the transition state, and the reaction is slow
- if activation energy is small, many collisions generate sufficient energy to reach the transition state, and the reaction is fast
Activation energy, $E_a$, is related to the reaction rate constant, $k$, by the Arrhenius equation

$$k = A e^{-E_a/RT}$$

- $A$ = frequency of collisions with correct geometry for reaction (sec$^{-1}$)
- $R$ = gas constant, $1.987 \times 10^{-3}$ kcal$\cdot$mol$^{-1}$$\cdot$K$^{-1}$
- $T$ = temperature in degrees Kelvin
Example: What is the activation energy for a reaction whose rate at 35°C is twice that at 25°C?

Solution:

- the ratio of rate constants $k_2$ and $k_1$ for the reaction at temperatures $T_2$ and $T_1$ is

\[
\frac{k_2}{k_1} = \frac{Ae^{-E_a/RT_2}}{Ae^{-E_a/RT_1}}
\]

- taking the ln of both sides and rearranging gives

\[
\ln \frac{k_2}{k_1} = \frac{E_a}{R} \left( \frac{1}{T_1} - \frac{1}{T_2} \right)
\]
• Substituting values and solving gives

\[
\ln \frac{2}{1} = \frac{E_a \text{ (kcal/mol)}}{1.987 \times 10^{-3} \text{ kcal\cdotmol}^{-1}\cdot\text{K}^{-1}} \left( \frac{1}{298\text{K}} - \frac{1}{308\text{K}} \right)
\]

\[E_a = 12.6 \text{ kcal/mol (52.7 kJ/mol)}\]
6 Developing a Mechanism

- Design experiments to reveal details of a particular chemical reaction

- Propose a set or sets of steps that might account for the overall transformation

- A mechanism becomes established when it is shown to be consistent with every test that can be devised

- This does mean that the mechanism is correct, only that it is the best explanation we are able to devise
6 Why Mechanisms?

- Framework within which to organize descriptive chemistry

- Intellectual satisfaction derived from constructing models that accurately reflect the behavior of chemical systems

- A tool with which to search for new information and new understanding
6 Electrophilic Additions

- Hydrohalogenation using HCl, HBr, HI
- Hydration using H₂O, H₂SO₄
- Halogenation using Cl₂, Br₂
- Halohydration using HOCl, HOBr
- Oxymercuration using Hg(OAc)₂, H₂O
Addition of $HX$

- Carried out with pure reagents or in a polar solvent such as acetic acid

- Addition is regioselective

- **Regioselective reaction:** a reaction in which one direction of bond-forming or bond-breaking occurs in preference to all other directions
6 Addition of HX

- H adds to the less substituted carbon

\[ \text{CH}_3\text{CH} = \text{CH}_2 + \text{HCl} \rightarrow \text{Propene} \]

\[ \begin{align*}
\text{CH}_3\text{CH} - \text{CH}_2 & \quad + \quad \text{CH}_3\text{CH} - \text{CH}_2 \\
& \quad \quad \quad \text{Cl} \quad \quad \text{H} \quad \quad \text{Cl} \\
& \quad \quad \quad \text{2-Chloropropane} \quad \quad \text{1-Chloropropane}
\end{align*} \]

- Markovnikov’s rule: in the addition of HX or H\(_2\)O to an alkene, H adds to the carbon of the double bond having the greater number of hydrogens.

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6 HCl + 2-Butene

A two-step mechanism

Step 1: formation of sec-butyl cation, a 2° carbocation intermediate

\[
\text{CH}_3\text{CH}==\text{CHCH}_3 + \text{HCl} \rightarrow \text{CH}_3\text{CH}==\text{CCHCH}_3^+ + \text{Cl}^-
\]

slow, rate-limiting step

sec-Butyl cation
6 HCl + 2-Butene

Step 2: reaction of the sec-butyl cation (a Lewis acid) with chloride ion (a Lewis base)

\[ \text{sec-Butyl cation (a Lewis acid)} \quad \text{fast} \quad \text{Cl}^- \quad \text{CH}_3\text{CHCH}_2\text{CH}_3 \quad \text{Cl}^- \quad \text{CH}_3\text{CHCH}_2\text{CH}_3 \]

Chloride ion (a Lewis base)  sec-Butyl cation (a Lewis acid)
6 Carbocations

- **Carbocation**: a species containing a positively charged carbon

- Carbocations are
  - classified as 1°, 2°, or 3° depending on the number of carbons bonded to the carbon bearing the positive charge
  - electrophiles, that is, they are “electron-lovers”
  - Lewis acids
Carbocation Structure

- Bond angles about the positively charged carbon are $120^\circ$
- Carbon uses $sp^2$ hybrid orbitals to form sigma bonds to the three attached groups
- The unhybridized 2p orbital lies perpendicular to the sigma bond framework and contains no electrons
6 Carbocation Stability

- A 3° carbocation is more stable than a 2° carbocation, and requires a lower activation energy for its formation.
- A 2° carbocation is, in turn, more stable than a 1° carbocation, and requires a lower activation energy for its formation.
- The methyl cation is so unstable that it is never observed in solution.
6 Carbocation Stability

- Relative stability

- Methyl cation (methyl)

- Ethyl cation (1°)

- Isopropyl cation (2°)

- tert-Butyl cation (3°)

Increasing carbocation stability
6 Carbocation Stability

We can account for the relative stability of carbocations if we assume that alkyl groups attached to the positively charged carbon are electron-releasing and thereby help delocalize the positive charge of the cation.

We account for this electron-releasing ability of alkyl groups by (1) the inductive effect, and (2) hyperconjugation.
6 Carbocation Stability

The inductive effect

- the electron-deficient carbon bearing the positive charge polarizes electrons of the adjacent sigma bonds toward it.
- the positive charge on the cation is not localized on the trivalent carbon, but delocalized over nearby atoms.
- the larger the volume over which the positive charge is delocalized, the greater the stability of the cation.
6 Carbocation Stability

- Hyperconjugation
  - partial overlap of the $\sigma$ bonding orbital of an adjacent C-H bond with the vacant 2p orbital of the cationic carbon delocalizes the positive charge and also the electrons of the adjacent $\sigma$ bond
  - replacing a C-H bond with a C-C bond increases the possibility for hyperconjugation
Addition of water is called hydration

Acid-catalyzed hydration of an alkene is regioselective - hydrogen adds to the less substituted carbon of the double bond

\[
\begin{align*}
\text{CH}_3\text{CH}=\text{CH}_2 & + \text{H}_2\text{O} \xrightarrow{\text{H}_2\text{SO}_4} \text{CH}_3\text{CH}-\text{CH}_2 \\
\text{Propene} & \quad \quad \text{2-Propanol}
\end{align*}
\]
6 Addition of H₂O

Step 1: proton transfer from solvent to the alkene

\[
\text{CH}_3\text{CH}=\text{CH}_2 + \text{H}^+ \text{H} \rightarrow \text{CH}_3\text{CHCH}_3 + \cdot\cdot\cdot\text{O}^-\text{H}^+
\]

A 2° carbocation intermediate

slow, rate-limiting step
6 Addition of H₂O

Step 2: a Lewis acid/base reaction forms an oxonium ion

\[ \text{CH}_3\text{CHCH}_3 + \text{H-O}^- \xrightarrow{\text{fast}} \text{CH}_3\text{CHCH}_3^+ \]

An oxonium ion

Step 3: proton transfer to solvent

\[ \text{CH}_3\text{CHCH}_3^+ \xrightarrow{\text{fast}} \text{CH}_3\text{CHCH}_3 + \text{H-O}^- \]

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6 C+ Rearrangements

- In electrophilic addition to alkenes, there is the possibility for rearrangement.

- **Rearrangement:** any change in connectivity of the atoms in a product compared with the connectivity of the same atoms in the starting material.
6 C+ Rearrangements

In addition of HCl to an alkene

\[
\text{CH}_3\text{CHCH=CH}_2 + \text{HCl} \rightarrow \text{CH}_3\text{CHCHCH}_3\text{Cl} + \text{CH}_3\text{CCH}_2\text{CH}_3\text{Cl}
\]

3-Methyl-1-butene

2-Chloro-3-methylbutane (expected) (40%)

2-Chloro-2-methylbutane (rearrangement) (60%)
6 C+ Rearrangements

In acid-catalyzed hydration of an alkene

\[
\text{CH}_3\text{CHCH}=\text{CH}_2 + \text{H}_2\text{O} \xrightarrow{\text{H}_2\text{SO}_4} \text{CH}_3\text{CCH}_2\text{CH}_3\text{OH}
\]

3-Methyl-1-butene \hspace{1cm} 2-Methyl-2-butanol
6 C⁺ Rearrangements

Driving force is rearrangement of a less stable carbocation to a more stable one

$$\text{CH}_3\text{CCH=CH}_2 + \text{H}^- \rightarrow \text{CH}_3\text{C}-\text{CHCH}_3 + \text{Cl}^-$$

3-Methyl-1-butene

A 2° carbocation intermediate

slow, rate-limiting step

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The less stable $2^\circ$ carbocation rearranges to a more stable $3^\circ$ one by shift of a hydrogen atom with its bonding electrons.

A $3^\circ$ carbocation intermediate.
6 C+ Rearrangements

Reaction of the more stable carbocation (a Lewis acid) with chloride ion (a Lewis base) completes the reaction

\[
\text{CH}_3\text{C-CH}_2\text{CH}_3 + \text{Cl}^- \rightarrow \text{CH}_3\text{C-CH}_2\text{CH}_3 \text{Cl}^-
\]

2-Chloro-2-methylbutane
Addition of Cl\(_2\) and Br\(_2\)  
- Carried out with either the pure reagents or in an inert solvent such as CCl\(_4\) or CH\(_2\)Cl\(_2\)  
- Addition is stereoselective  
- **Stereoselective reaction**: a reaction in which one stereoisomer is formed or destroyed in preference to all others than might be formed or destroyed.
6 Addition of Cl₂ and Br₂

2-Butene + Br₂ → CH₃CH-CHCH₃ 2,3-Dibromobutane

Cyclohexene + Br₂ → trans-1,2-Dibromo-cyclohexane
Addition of Cl₂ and Br₂

Addition involves a two-step mechanism:

Step 1: formation of a bridged bromonium ion intermediate

A bridged bromonium ion

+ Br⁻
Addition of \( \text{Cl}_2 \) and \( \text{Br}_2 \)

Step 2: Attack of halide ion from the opposite side of the three-membered ring

Anti addition
For a cyclohexene, anti coplanar addition corresponds to trans-diaxial addition.

```
\[ \text{trans-Diaxial (less stable)} \quad \rightarrow \quad \text{trans-Diequatorial (more stable)} \]
```
Addition of HOCl and HOBr

- Treatment of an alkene with Br₂ or Cl₂ in water forms a halohydrin

- **Halohydrin**: a compound containing -OH and -X on adjacent carbons

\[
\text{CH}_3\text{CH} = \text{CH}_2 \quad \xrightarrow{\text{Cl}_2, \text{H}_2\text{O}} \quad \text{CH}_3\text{CH}-\text{CH}_2\quad + \quad \text{HCl}
\]

1-Chloro-2-propanol (a chlorohydrin)
Reaction is both regioselective (anti addition) and stereoselective (OH to the more substituted carbon)

1-Methylcyclopentene $\xrightarrow{\text{Br}_2, \text{H}_2\text{O}}$ 2-Bromo-1-methylcyclopentanol (anti addition of -OH and -Br)
6 Addition of HOCl and HOBr

Step 1: formation of a bridged-halonium ion intermediate

bridged bromonium ion

minor contributing structure
6 Addition of HOCl and HOBr

Step 2: attack of H$_2$O on the more substituted carbon and opening of the three-membered ring

Anti addition of Br and H$_2$O
6 Oxymercuration/Reduction

Oxymercuration: the addition of Hg(II) to one carbon of a double bond and oxygen to the other

\[
\text{CH}_3\text{CH}=\text{CHCH}_3 + \text{Hg(OAc)}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{CHCHCH}_3\text{HgOAc} + \text{CH}_3\text{CO}_2\text{H}
\]

- 2-Butene
- Mercury(II) acetate
- An organomercury compound
- Acetic acid
Reduction with NaBH₄ replaces Hg by H

\[ \text{CH}_3\text{CHCHCH}_3 + \text{CH}_3\text{CO}_2\text{H} + \text{Hg} \rightarrow \text{CH}_3\text{CHCHCH}_3 + \text{H}_2 \]

2-Butanol

Acetic acid
Addition of Hg(II) and oxygen is anti coplanar stereoselective

Cyclopentene  $\xrightarrow{\text{Hg(OAc)}_2, \text{H}_2\text{O}}$  (Anti addition of -OH and -HgOAc)
6 Oxymercuration/Reduction

Step 1: dissociation of mercury (II) acetate to give AcOHg\(^+\), a Lewis acid

\[ \text{AcO-Hg-OAc} \rightarrow \text{AcO-Hg}^+ + \text{AcO}^- \]

Step 2: attack of AcOHg\(^+\) on the double bond to give a bridged mercurinium ion intermediate in which the two electrons of the pi bond form a two-atom three-center bond
6 Oxymercuration/Reduction

(a minor contributor) (the major contributor)
Step 3: stereoselective and regioselective attack of $\text{H}_2\text{O}$ on the bridged intermediate

Anti stereoselective addition of $\text{HgOAc}$ and $\text{HOH}$
6 Oxymercuration/Reduction

Step 4: proton transfer to solvent completes oxymercuration

The fact that oxymercuration occurs without rearrangement indicates that the intermediate is not a true carbocation, but rather a resonance hybrid closely resembling a bridged mercurinium ion intermediate.
Regioselectivity is accounted for by at least some carbocation character in the bridged intermediate.

Stereoselectivity is accounted for by anti attack on the bridged intermediate.
6 Hydroboration/Oxidation

- **Hydroboration**: the addition of borane, BH$_3$, to an alkene to form a trialkylborane

  ![Chemical Structure](image)

  Borane $\rightarrow$ A trialkylborane

- **Borane dimerizes to diborane, B$_2$H$_6$**

  ![Chemical Structure](image)

  Borane $\leftrightarrow$ B$_2$H$_6$  Diborane
Borane forms a stable complex with ethers such as THF. The reagent is used most often as a commercially available solution of BH$_3$ in THF.

\[2 \text{THF} + \text{B}_2\text{H}_6 \rightarrow 2 \text{BH}_3\cdot\text{THF}\]

Tetrahydrofuran (THF)                      BH$_3$•THF
6 Hydroboration/Oxidation

Hydroboration is both regioselective (boron to the less hindered carbon) and stereoselective (syn addition)

1-Methylcyclopentene

\[ \text{BH}_3 \rightarrow \text{BR}_2 \]

(Syn addition of \( \text{BH}_3 \) (R = 2-methylcyclopentyl)}
Mechanism involves concerted regioselective and stereoselective addition of B and H to the carbon-carbon double bond.

Bond breaking and bond forming occur simultaneously.

Boron adds to the less substituted carbon of the double bond.
Trialkylborananes are rarely isolated. Oxidation with alkaline hydrogen peroxide gives an alcohol and sodium borate

\[(\text{RO})_3\text{B} + 3\text{NaOH} \rightarrow 3\text{ROH} + \text{Na}_3\text{BO}_3\]

A trialkylborate \hspace{3cm} An alcohol

The result of hydroboration/oxidation is regioselective and stereoselective hydration of a carbon-carbon double bond
Hydroboration/Oxidation

1-Methylcyclopentene

Atrialkylborane
(R = 2-methylcyclopentyl)

H₂O₂
NaOH

trans-2-Methyl-cyclopentanol
6 Oxidation/Reduction

- **Oxidation:** the loss of electrons
- **Reduction:** the gain of electrons

Recognize using a balanced half-reaction

1. write a half-reaction showing one reactant and its product(s)
2. complete a material balance. Use H₂O and H⁺ in acid solution; use H₂O and OH⁻ in basic solution
3. complete a charge balance using electrons, e⁻
Oxidation with OsO$_4$

Oxidation by OsO$_4$ converts an alkene to a glycol, a compound with -OH groups on two adjacent carbons

- oxidation is syn stereoselective

1. OsO$_4$
2. NaHSO$_3$

A cis glycol
Intermediate is a cyclic osmic ester containing a five-membered ring

(A cyclic osmate ester)
Reduction of the osmic ester with NaHSO$_3$ gives the glycol and a reduced form of osmium.

\[
\text{cis-1,2-Cyclopentanediol (a cis glycol)} + \text{reduced forms of osmium}
\]
OsO$_4$ is both expensive and highly toxic.

It is used in catalytic amounts with another oxidizing agent to reoxidize its reduced forms and, thus, recycle OsO$_4$.

- Hydrogen peroxide
- $t$-Butyl hydroperoxide (t-BuOOH)
Treatment of an alkene with ozone followed by a weak reducing agent cleaves the C=C and forms two carbonyl groups in its place.

$$\text{CH}_3\text{C}=\text{CHCH}_2\text{CH}_3 \xrightarrow{1. \ O_3} \xrightarrow{2. \ (\text{CH}_3)_2\text{S}}$$

2-Methyl-2-pentene

$$\text{CH}_3\text{CCH}_3 + \text{HCCH}_2\text{CH}_3$$

Propanone (a ketone)  Propanal (an aldehyde)
6 Reduction of Alkenes

- Most alkenes react with H₂ in the presence of a transition metal catalyst to give alkanes.

\[
\text{Cyclohexene} + \text{H}_2 \xrightarrow{\text{Pt}} \text{Cyclohexane}
\]

- Commonly used catalysts are Pt, Pd, Ru, and Ni.

- The process is called catalytic reduction or, alternatively, catalytic hydrogenation.
6 Reduction of Alkenes

Most common pattern is syn stereoselectivity

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

1,2-Dimethyl-cyclohexene → 70% to 85% cis-1,2-Dimethyl-cyclohexane + 30% to 15% trans-1,2-Dimethyl-cyclohexane
6 Reduction of Alkenes

Mechanism of catalytic hydrogenation

- $\text{H}_2$ is absorbed on the metal surface with formation of metal-hydrogen bonds
- the alkene is also absorbed with formation of metal-carbon bonds
- a hydrogen atom is transferred to the alkene forming one new C-H bond
- a second hydrogen atom is transferred forming the second C-H bond
In catalytic hydrogenation, there is net conversion of one pi bond to one sigma bond.

Catalytic hydrogenation of an alkene is exothermic.

Heats of hydrogenation depend on the degree of substitution of the carbon-carbon double bond.
## ΔH° of Hydrogenation

<table>
<thead>
<tr>
<th>Name</th>
<th>Structural Formula</th>
<th>ΔH° (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ethylene</td>
<td>CH₂ =CH₂</td>
<td>-32.8</td>
</tr>
<tr>
<td>propene</td>
<td>CH₃ CH=CH₂</td>
<td>-30.1</td>
</tr>
<tr>
<td>1-butene</td>
<td>CH₃ CH₂ CH=CH₂</td>
<td>-30.3</td>
</tr>
<tr>
<td>cis-2-butene</td>
<td>CH₃ CH=CHCH₃</td>
<td>-28.6</td>
</tr>
<tr>
<td>trans-2-butene</td>
<td>CH₃ CH=CHCH₃</td>
<td>-27.6</td>
</tr>
<tr>
<td>2-methyl-2-butene</td>
<td>(CH₃)₂ C=CHCH₃</td>
<td>-26.9</td>
</tr>
<tr>
<td>2,3-dimethyl-2-butene</td>
<td>(CH₃)₂ C=C(CH₃)₂</td>
<td>-26.6</td>
</tr>
</tbody>
</table>
The greater the degree of substitution of a double bond, the lower its heat of hydrogenation.

- the greater the degree of substitution, the more stable the double bond

The heat of hydrogenation of a trans alkene is lower than that of the isomeric cis alkene.

- a trans alkene is more stable than its isomeric cis alkene. The difference is due to nonbonded interaction strain in the cis alkene.
6 $\Delta H^\circ$ of Hydrogenation

cis-2-Butene
(less stable)

trans-2-Butene
(more stable)
Conjugated Diene: the double bonds are separated by one single bond

\[
\text{CH}_2 = \text{CHCH} = \text{CHCH}_3
\]
1,3-Pentadiene
(a conjugated diene)

\[
\text{CH}_2 = \text{CHCH}_2 \text{CH} = \text{CH}_2 \quad \text{CH}_2 = \text{C} = \text{CHCH}_2 \text{CH}_3
\]
1,4-Pentadiene
(an unconjugated diene) 1,2-Pentadiene
(a cumulated diene)
Conjugated Dienes

From heats of hydrogenation, we determine that conjugated dienes are more stable than isomeric unconjugated dienes by approximately 3.5 to 4.0 kcal/mol

<table>
<thead>
<tr>
<th>Name</th>
<th>Structural Formula</th>
<th>$\Delta H^\circ$ (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-butene</td>
<td>CH$_2 =$CHCH$_2$CH$_3$</td>
<td>-30.3</td>
</tr>
<tr>
<td>1,3-butadiene</td>
<td>CH$_2 =$CHCH=CH$_2$</td>
<td>-56.5</td>
</tr>
</tbody>
</table>
the extra stability of conjugated dienes arises because of the additional delocalization of electron density over the four parallel 2p atomic orbitals
Compounds containing conjugated carbon-carbon and carbon-oxygen double bonds are also more stable than their unconjugated isomers.

2-Cyclohexenone (more stable)

3-Cyclohexenone (less stable)
In several of the reactions presented in this chapter, stereocenters are created.

Where one or more stereocenters are created, is the product

- one enantiomer and, if so, which one?
- a pair of enantiomers?
- a meso compound?
- a mixture of stereoisomers?
- or what?
Which of the three possible stereoisomers of 2,3-dibromobutane are formed in the addition of bromine to trans-2-butene?

- the three possible stereoisomers for this compound are a pair of enantiomers and a meso compound
Reaction of bromine with the alkene forms a cyclic bromonium ion intermediate which is then opened by attack of bromide ion from the side opposite the bromine bridge.
6 Reaction Stereochemistry

(2S,3R)-2,3-Dibromo-butane

(2R,3S)-2,3-Dibromo-butane

identical; a meso compound
How many and what kind of stereoisomers are formed in the oxidation of cis-2-butene by OsO₄?

three stereoisomers are possible for 2,3-butanediol; a meso compound and a pair of enantiomers
Reaction Stereochemistry

(2S,3R)-2,3-Butanediol

(2R,3S)-2,3-Butanediol

identical; a meso compound
How many and what kind of stereoisomers are formed in the oxidation of trans-2-butene by OsO₄?
6 Reaction Stereochemistry

(2R,3R)-2,3-Butanediol

(2S,3S)-2,3-Butanediol

a pair of enantiomers; a racemic mixture
Enantiomerically pure products can never be formed from achiral starting materials and reagents.

An enantiomerically pure product can be generated in a reaction if at least one of the reactants is enantiomerically pure, or if the reaction is carried out in an achiral environment.
End Chapter 6