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Organic Chemistry

Chapter 16

Conjugation and Resonance

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Chapter 16

Conjugation and Resonance

Chapter Outline

16.1 Naming Compounds with Multiple Functional Groups
Nomenclature of compounds with multiple functional groups

16.2 Conjugated Dienes
An introduction to the interaction of double bonds separated by one single bond

16.3 The Allyl Group and Resonance
The special reactivity of the allyl group and the stabilization of the allyl carbocation

16.4 Conjugate Addition Reactions
Reactivity of a conjugated diene

16.5 Double Bonds Conjugated With Carbonyl Groups
Reactivity of a carbonyl group conjugated with a double bond

16.6 The Diels-Alder Reaction
An introduction to the Diels-Alder cycloaddition reaction

16.7 Orbital Symmetry and the Diels-Alder Reaction
The molecular orbital requirements for the Diels-Alder reaction

16.8 Synthesis with the Diels-Alder Reaction
Using the Diels-Alder reaction in synthesis

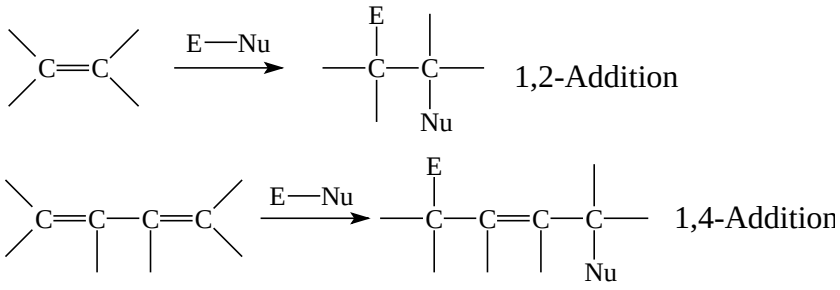
Objectives

- ✔ Know the IUPAC rules for naming molecules with two functional groups
- ✔ Understand the conjugated π molecular orbitals in a diene
- ✔ Understand the orbitals involved in stabilizing an allylic carbocation
- ✔ Compare the reactions of conjugated carbonyl compounds with conjugated dienes
- ✔ Be able to write a mechanism for the Diels-Alder reaction
- ✔ Use the Diels-Alder reaction in organic synthesis

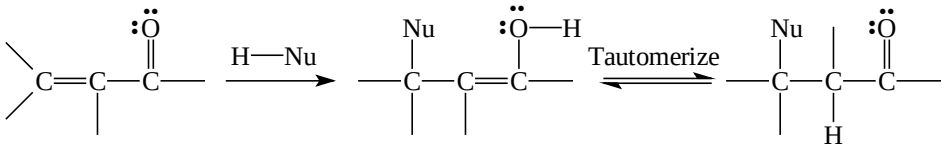
There is no excellent beauty that hath not some strangeness in the proportion.
—Francis Bacon

The simplest conjugated system is a pair of unsaturated, or double, bonds separated by one saturated, or single, bond. A compound that contains a conjugated diene acts differently than one that contains an unconjugated diene. An unconjugated diene is a compound that contains two double bonds separated by more than one single bond. The double bonds in an unconjugated diene are far enough apart that they have very little effect on each other; whereas, the double bonds in a conjugated diene are so close that they interact electronically with each other. This interaction determines many of the chemical properties of conjugated organic compounds. Conjugation also stabilizes chemical compounds in comparison to similar nonconjugated compounds.

This chapter examines several conjugated systems and the distinctive reactions that they undergo. In many of these reactions, the conjugated systems behave as if they are a single functional group. For example, a conjugated diene undergoes a 1,4-addition reaction analogous to the 1,2-additions discussed in Chapter 14.



A conjugated carbonyl system undergoes addition reactions analogous to those covered in Chapter 7.



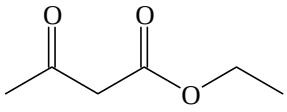
1,4-Addition product

Most importantly, this chapter serves as a foundation to Chapters 17 and 18, which discuss the benzene ring. The benzene ring is an especially stable conjugated system. Understanding the unique stabilization in benzene will help you understand the chemistry of the aromatic family, a very important class of organic compounds.

16.1 Naming Compounds with Multiple Functional Groups

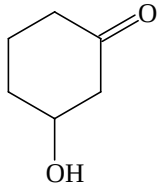
When a molecule contains two or more functional groups, you must choose among them for the parent name. Not only the parent name but the prefix, suffix, and functional group numbering depend on that choice. To maintain consistency, use the IUPAC established priority order to direct you in choosing the parent name.

The highest priority goes to the functional groups that always terminate a carbon chain. For example, carboxylic acids and their derivatives and the aldehydes are examples of groups that always terminate a carbon chain. The following molecule contains an ester and a ketone. Because the ester is always at the end of the chain and the ketone is not, the ester determines the parent name. Thus the ester group name is the suffix used in naming the compound. The IUPAC name is ethyl 3-oxobutanoate.



Ethyl 3-oxobutanoate

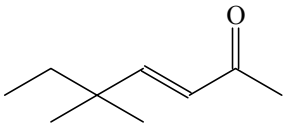
The next priority goes to those functional groups that can bond to the parent molecule at any point on that molecule. Examples of this type are ketones, alcohols, and amines. The following molecule contains a ketone and an alcohol. The ketone has higher priority and thus the molecule is 3-hydroxycyclohexanone.



3-Hydroxycyclohexanone

Combining the —ene *and* —yne *suffixes is introduced in Section 2.9, page 000.*

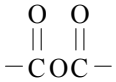
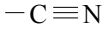
Next in priority are the alkenes and alkynes. You may use the *—ene* and *—yne* endings with any of the other suffixes. Note, however, that you cannot combine any of the other suffixes. All the others must be used alone. The following molecule contains an alkene as well as a ketone. Note that the IUPAC name uses *both* suffixes.



E-5,5-dimethyl-3-hepten-2-one

Finally, the lowest priority is assigned to the groups that have no suffix such as halogens, nitro, and alkyl groups.

To form the name of a compound with multiple functional groups, name the parent compound using the suffix of the group with the highest priority, then list the other groups as substituent groups giving them their prefix annotations. Table 16.1 summarizes the priority rules for IUPAC nomenclature by listing the functional groups in their priority order.

Functional Group	Structure	Suffix	Prefix
Carboxylic acid		—oic acid	carboxy—
Carboxylic acid Anhydride		—oic anhydride	——
Ester		alkyl —oate	alkoxycarbonyl— (or carbalkoxy—)
Acyl halide		—oyl halide	haloalkanoyl—
Amide		—amide	carbamoyl—
Nitrile		—nitrile	cyano—
Aldehyde		—al	alkanoyl—
Ketone		—one	oxo—
Alcohol	C—OH	—ol	hydroxy—
Thiol (or mercaptan)	C—SH	—thiol	mercapto—

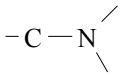
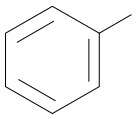
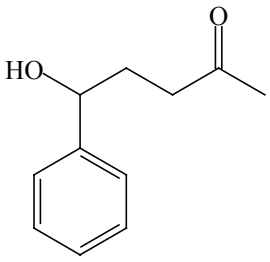
Functional Group	Structure	Suffix	Prefix
Ether	C—O—C	(ether)	oxa— (in a ring) (or alkoxy—)
Amine		—amine	amino— (or aza— in a ring)
Sulfide	C—S—C	(sulfide)	alkylthio— (or thia— in a ring)
Disulfide	C—S—S—C	(disulfide)	alkyldithio— (or dithia— in a ring)
Aromatic		—benzene	phenyl—
Alkene	C=C	—ene	alkenyl—
Alkyne		—yne	alkynyl—
Halide	C—X	——	halo—
Nitro	—NO_2	——	nitro—

Table 16.1. IUPAC nomenclature summary with the functional groups arranged in order of decreasing priority.

Solved Exercise 16.1

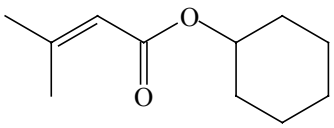
Name the following molecules using IUPAC rules.

a)



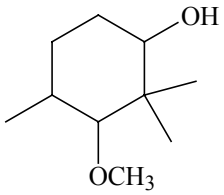
Solution
This molecule has two functional groups: a ketone and an alcohol. According to Table 16.2, the ketone has a higher priority than the alcohol. Thus, the name of the molecule has the *–one* suffix. The name is 5-hydroxy-5-phenyl-2-pentanone.

b)



Solution
This molecule contains an ester and a double bond. In this case, both modify the suffix of the name. The name is cyclohexyl 3-methyl-2-butenoate.

c)

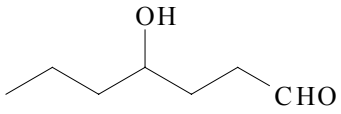


Solution
This molecule contains an alcohol and an ether. The alcohol is higher priority, so it determines the suffix of the name. The ether is named as a substituent. The compound is 3-methoxy-2,2,4-trimethylcyclohexanol.

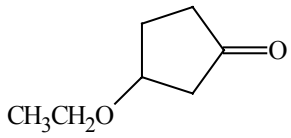
Exercise 16.1

Name the following molecules using IUPAC rules.

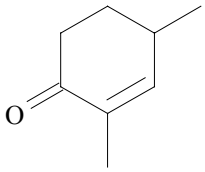
(a)



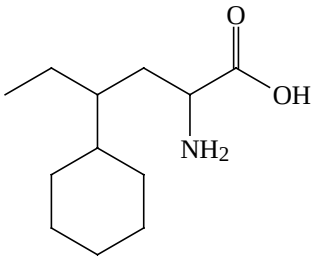
(b)



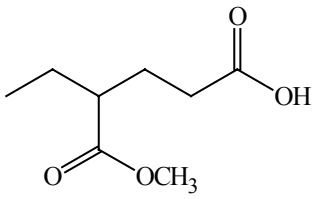
(c)



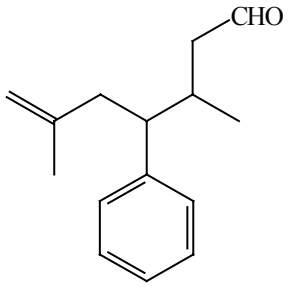
(d)



(e)



(f)



Sample solution

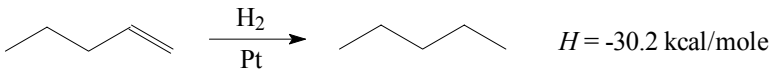
(b) 3-Ethoxycyclopentanone

16.2 Conjugated Dienes

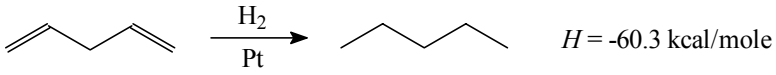
Heats of hydrogenation are introduced in Section 13.3, page 000.

There are three characteristics that make conjugated dienes different from unconjugated dienes are: a lower than expected heat of hydrogenation for the compound, a shorter than expected C—C single bond between the two double bonds, and a restricted rotation about that C—C single bond. Chapter 13 points out that the lower the heat of hydrogenation of a compound, the more stable that compound is in comparison to a similar compound. The heats of hydrogenation of various alkenes show that a *trans* alkene is more stable than a *cis* alkene, and a *cis* alkene is more stable than a terminal alkene. The heat of hydrogenation for a *trans* alkene is approximately 1 kcal/mole less than the heat of hydrogenation for a *cis* alkene, and the heat of hydrogenation for a *cis* alkene is about 1.5 kcal/mole lower than the heat of hydrogenation of a terminal alkene. This makes the difference in the heats of hydrogenation between a *trans* alkene and its terminal isomer about 2.5 kcal/mole.

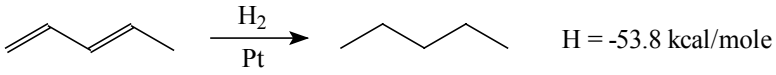
In a diene with two isolated double bonds, the total heat of hydrogenation for that molecule is close to the sum of the two individual double bonds. For example, the heat of hydrogenation of 1-pentene is –30.2 kcal/mole.



For 1,4-pentadiene, the heat of hydrogenation is –60.3 kcal/mole, which is almost exactly twice the total of 1-pentene.



In a conjugated diene, the heat of hydrogenation for the double bonds is less than the sum of the two individual bonds. For example, *E*-1,3-pentadiene contains a *trans* double bond and a terminal double bond. The heat of hydrogenation for 1-pentene (a terminal double bond) is –30.2 kcal/mole, and the heat of hydrogenation of *E*-2-pentene (a *trans* double bond) is –27.3 kcal/mole. Adding these two values, you get the sum of –57.5 kcal/mole, which is the predicted heat of hydrogenation for *E*-1,3-pentadiene. However, the experimental data shows its actual heat of hydrogenation is –53.8 kcal/mole. The amount of heat given off is less than the sums of the individual double bonds. This value indicates that *E*-1,3-pentadiene is 3.7 kcal/mole more stable than expected. Table 16.1 summarizes these heats of hydrogenation.



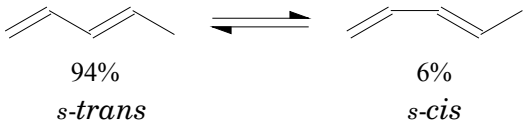
Compound	Observed heat of hydrogenation (kcal/mole)	Predicted heat of hydrogenation (kcal/mole)
1-Pentene	–30.2	------
E-2-Pentene	–27.3	------
E-1,3-Pentadiene	–53.8	–57.5
1,4-Pentadiene	–60.3	–60.4

Table 16.1. The heats of hydrogenation for several various pentenes and pentadienes.

The second characteristic that makes a conjugated diene different from an unconjugated diene is the shorter than expected C—C single bond between the two double bonds. This bond is shorter because the two conjugated double bonds interact with each other. For example, the C2—C3 bond length in *E*-1,3-pentadiene is 146 pm compared with 154 pm in a typical C—C single bond. A typical double bond is 133 pm long. Because the C2—C3 bond is shorter than a normal single bond and longer than a normal double bond, it has some double bond character, further illustrating the interaction between the two double bonds.

The third characteristic of a conjugated diene is the restricted rotation about the C—C single bond between the two double bonds. The most stable conformation of conjugated dienes is the ***s-trans* conformation**. In the ***s-cis* conformation**, the double bonds are on the same side of the single bond. At equilibrium, 94% of *E*-1,3-pentadiene is in the *s-trans* conformation, and 6% is in the *s-cis* conformation.

The letter s *refers to the conformation of the double bonds with the single bond between them. In the* s-trans *conformation the double bonds are on the opposite sides of the single bond. In the* s-cis *conformation, the double bonds are on the same side.*



The rotational energy barrier between the *s-trans* conformation and the s-*cis* conformation is 6.7 kcal/mole. The rotational energy barrier of *E*-1,3-pentadiene is approximately 2-3 kcal/mole higher than for the free rotation about a single bond.

The best explanation for the differences between unconjugated dienes and conjugated dienes comes from an understanding of what happens in their respective molecular orbitals. With the *E*-1,3-pentadiene, carbon atoms 1 through 4 are sp^2 hybridized and in the planar *s-cis* or *s-trans* conformations. This arrangement, as shown in Figure 16.1, means that *all four* carbon atoms have overlapping *p* orbitals.

For a review of molecular orbitals, read Section 1.6, page 000.

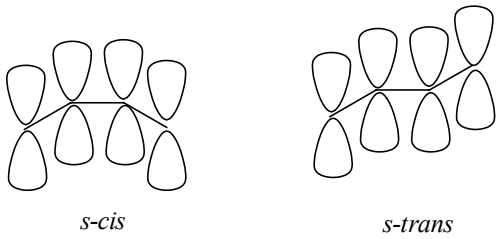


Figure 16.1. Overlap of orbitals in the *s-cis* and *s-trans* conformations of a diene.

As a result of hybridization and the overlapping *p* orbitals, the electrons in the two π bonds are **delocalized**, or spread, over all four carbons. This delocalization creates some π bond character in the σ bond between C2 and C3. The higher than expected rotational energy barrier and the shorter than normal single bond are evidence for the partial π bond.

Delocalized electrons are in an orbital that spreads over more than two atoms.

This discussion is an extension of the discussion begun in Section 1.8, page 000.

Before considering the MO construction of a conjugated diene in greater depth, look at the formation of an isolated double bond, such as the one in ethene. Keep in mind that the individual double bonds in an unconjugated diene act similarly to the double bond in an alkene. When ethylene forms, the two *p* orbitals of the two carbon atoms overlap and form both a π (bonding) and a π* (antibonding) molecular orbital, as shown in Figure 16.2. Each *p* atomic orbital has two lobes, and the wave function (ψ) gives a positive sign to one lobe and a negative sign to the other. The π bonding molecular orbital of ethylene forms when the *p* atomic orbitals overlap with the like signs of the wave function in the bonding region between the two nuclei. This type of overlap is called a **constructive overlap**. Formation of the π* antibonding molecular orbital occurs when the *p* atomic orbitals with opposite signs for the wave functions overlap in the bonding region. This type of overlap is called a **destructive overlap**.

With constructive overlap, the signs of ψ are the same in overlap.

With destructive overlap, the signs of ψ are opposite.

Conservation of Molecular Orbitals

Recall from Chapter 1 that whatever numbers of atomic orbitals combine to form molecular orbitals, the same number of molecular orbitals results. In this way no orbitals are gained or lost. As the MOs form, they distribute their energies symmetrically above and below the energies of the starting atomic orbitals. Thus, half of the molecular orbitals are bonding, and half are antibonding. When the electrons populate the newly formed MOs, the lowest energy MOs are filled first. Generally these lowest energy MOs are lower energy than the energy level of the original *p* orbitals. On those few occasions when electrons populate the antibonding MOs, they have a higher energy than they did in their original *p* orbitals. In the ground state of ethylene, the bonding molecular orbital has two electrons, and the antibonding molecular orbital has none.

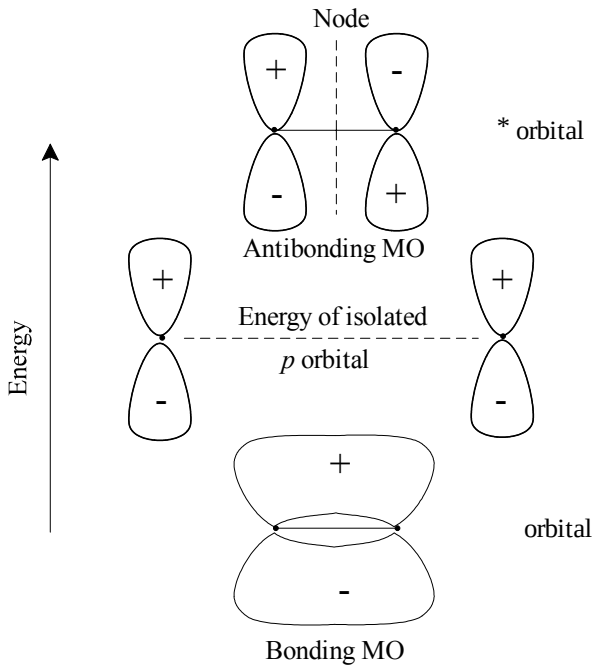


Figure 16.2. The formation of the π and π* molecular orbitals from isolated *p* atomic orbitals.

Now, extend the above idea of the formation of a molecular orbital to the formation of a π molecular orbital for a conjugated diene. The construction of the π molecular orbitals for a conjugated diene requires that four *p* atomic orbitals from the four carbon atoms overlap. The overlap of these orbitals leads to four π MOs, each of which encompasses all four atoms that contributed the *p* orbitals. The two lower energy π MOs are filled with two electrons each, whereas the two higher energy π MOs remain empty. Figure 16.3 shows the energy relationship between the constituent atomic orbitals and the molecular orbitals.

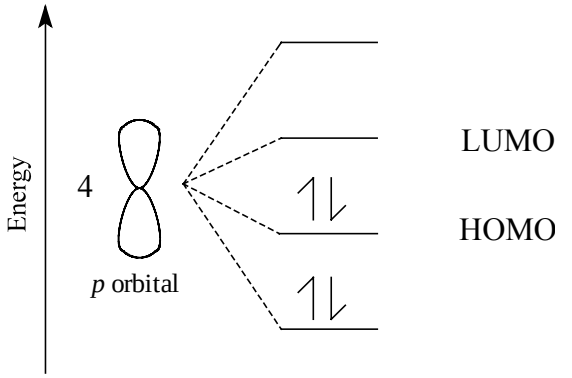


Figure 16.3. The energy relationship between the constituent *p* orbitals and the π MOs of a conjugated diene. The HOMO and LUMO MOs are marked.

With the formation of conjugated dienes, the distinction between bonding and antibonding orbitals blurs. As shown in Figure 16.4, molecular orbitals π_2 through π_4 have one or more antibonding nodes, whereas π_1 has none. The π_1 molecular orbital consists only of bonding overlaps between the constituent atomic orbitals of 1,3-pentadiene. As a result, the π_1 molecular orbital is very stable. The π_{1-4} MOs of a conjugated diene are called **delocalized molecular orbitals** because they extend over more than two atoms. MOs that involve only two atoms are called **localized molecular orbitals**.

Delocalized molecular orbitals extend over more than two atoms; localized MOs involve only two atoms.

The π_1 molecular orbital of a conjugated diene is lower in energy than the π_1 molecular orbital of an unconjugated diene or alkene. The π_1 molecular orbital of a conjugated system also exhibits the other two special characteristics of a conjugated system: **planar conformation** and a shorter than typical single bond between C2—C3 caused by the π character of the σ bond. This MO has the lowest energy of the four MOs formed in a conjugated system, so it fills with electrons before any of the other levels.

The planar conformation is the more stable conformation because of the restricted rotation between C2 and C3.

The next lowest energy π molecular orbital, the π_2 MO, involves bonding overlap between C1—C2 and C3—C4 along with an antibonding overlap (node) between C2 and C3. The π_2 MO is higher in energy than the π_1 MO and, because of the node between C2 and C3, the π_2 MO is weaker than the π_1 MO. After the π_1 MO fills with electrons, the π_2 MO then fills. The π_2 MO is the highest occupied molecular orbital (abbreviated HOMO).

The next π MO, the π_3 MO, involves a bonding overlap between C2—C3 and an antibonding overlap between C1—C2 and C3—C4. In energy, the π_3 molecular orbital is the lowest unoccupied molecular orbital (LUMO). The π_4 MO involves all antibonding overlaps between adjacent carbons. In energy, the π_4 MO is the highest unoccupied molecular orbital.

There are a total of four electrons distributed among these four conjugated MOs. In the ground, or lowest energy, state both the π_1 and the π_2 MOs are occupied. Each contains two electrons. The higher energy MOs are unoccupied. Most stable molecules follow this arrangement of filled lower level molecular orbitals and unfilled higher level molecular orbitals.

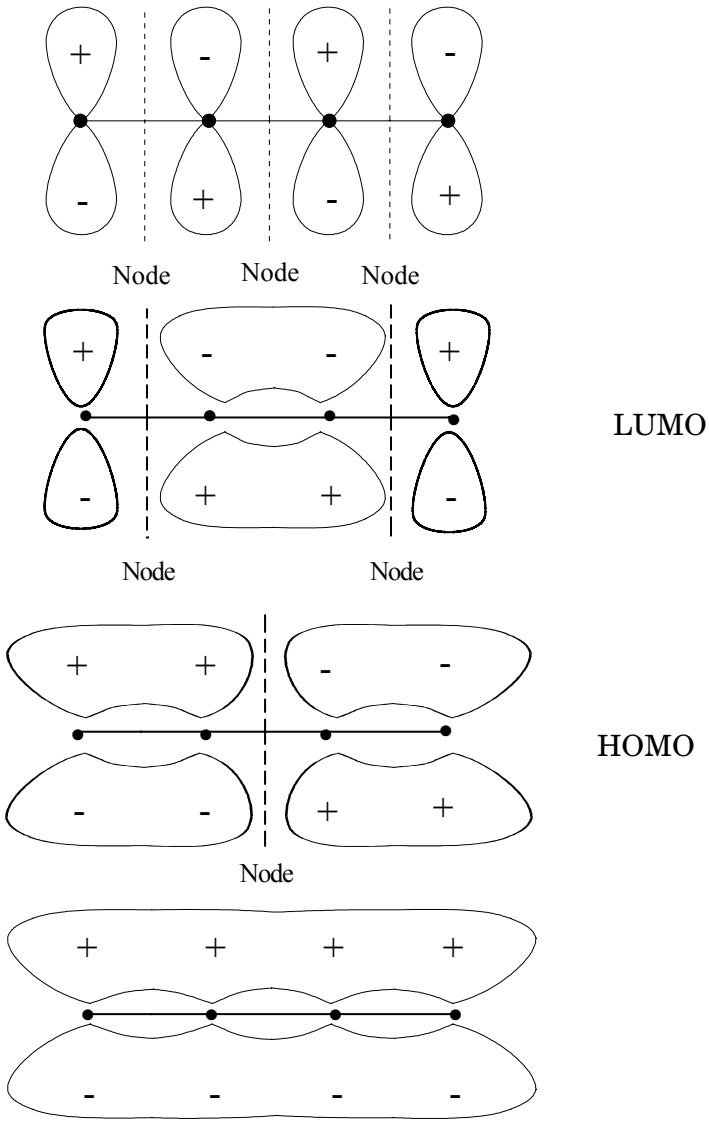


Figure 16.4. The four molecular orbitals in a conjugated π system. The energy of the molecular orbitals increases from π_1 to π_4.

Notice how the nodes in each of the π molecular orbitals are symmetrically, or equally, distributed. The nodes in a molecular orbital are always symmetrically distributed. For example, the π_3 molecular orbital has two nodes equidistant from the center and ends of the orbital. When you draw π molecular orbitals, draw only MOs with symmetrically distributed nodes.

Exercise 16.2

Arrange the following compounds in order of increasing heat of hydrogenation.

1,3-hexadiene; 1,4-hexadiene; 1,5-hexadiene; and 2,4-hexadiene

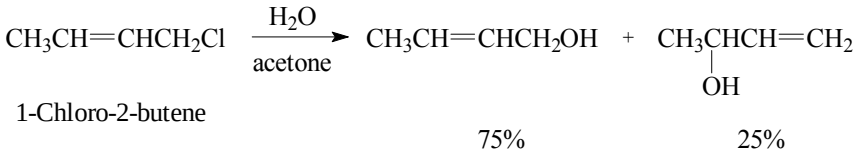
16.3 The Allyl Group and Resonance

Resonance is another important factor in the body of knowledge necessary to understand the discussion of the benzene ring in Chapters 17 and 18. This section looks at the part that resonance plays in two surprising aspects of reactions of **allyl halides**.

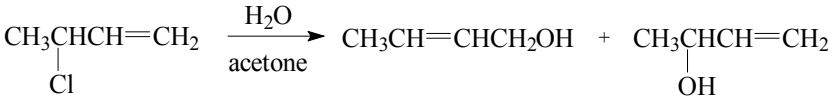
An allyl halide has a double bond and a halogen attached to the same carbon. The simplest allyl halide is 3-halo-1-propene (CH_2=$CHCH_2X$).

The first surprise is that a primary allyl halide reacts as readily as a tertiary alkyl halide. 1-Chloro-2-butene is a primary alkyl halide but, because it contains a double bond adjacent to the carbon bearing the halogen, it is more precisely an allyl halide. With this double bond, 1-chloro-2-butene becomes nearly as reactive as *tert*-butyl chloride in S_N1 reactions. The second surprise is that when 1-chloro-2-butene reacts in aqueous acetone, it forms the same two products as the reaction of 3-chloro-1-butene with aqueous acetone.

Recall from Chapter 12 that in S_N1 reactions with alkyl halides, tertiary alkyl halides are the most reactive, then come secondary alkyl halides, followed by primary alkyl halides.



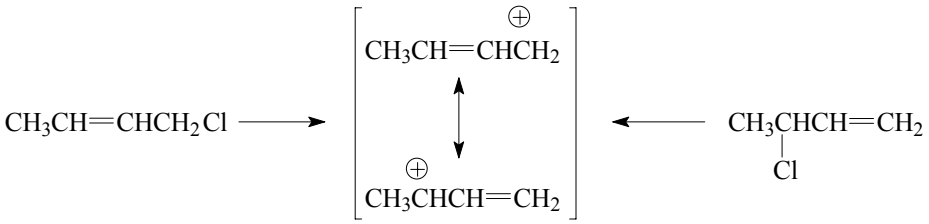
1-Chloro-2-butene 75% 25%



3-Chloro-1-butene 75% 25%

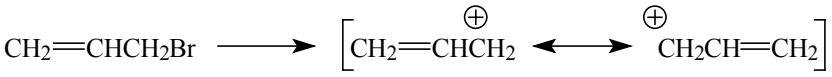
Both reactions form the same two products because the two substrates, 1-chloro-2-butene and 3-chloro-1-butene, contain a Cl on the carbon adjacent to the double bond. When each compound loses the Cl, both form the same resonance-stabilized carbocation intermediate. Chemists call this type of carbocation an **allylic carbocation**.

An allylic carbocation has a double bond attached to the positively charged carbon.



An allylic carbocation

The term allylic carbocation is derived from the common name of the simplest member of this type of resonance-stabilized carbocation, the allyl carbocation.



Allyl bromide Allyl carbocation

Resonance makes the allyl carbocation more stable than a simple primary carbocation because the positive charge is *delocalized* over two carbon atoms. A primary allylic carbon with a positive charge is nearly as stable as a simple tertiary carbocation. A secondary allylic carbocation is *more* stable than a simple tertiary carbocation.

Resonance Contributors

Remember that a compound does not "resonate" among its various resonance contributors. The molecule is a hybrid structure of all of the possible resonance contributors. At all times the compound possesses the characteristics of all the contributors. No resonance structure has an independent existence. Resonance structures were designed as an aid to understanding the structure and reactivity of the actual molecule. Review the rules for drawing resonance contributors in Section 1.13 (p. 000).

The formation of the MOs helps to explain why allyl halides behave the way they do. The molecular orbitals of an allylic carbocation form in an S_N1 reaction in aqueous acetone and with an allylic halide. The double bond of the allylic halide assists the chloride ion to leave. With the chloride ion gone, the compound becomes a carbocation with an empty *p* orbital. This empty *p* orbital then lines up with the two orbitals (π and π^*) of the double bond. Because these three orbitals are parallel, they overlap to form three new molecular orbitals. Thus, an allylic carbocation more stable than an ordinary carbocation. Figure 16.5 shows their relative energy levels, and Figure 16.6 shows these molecular orbitals.

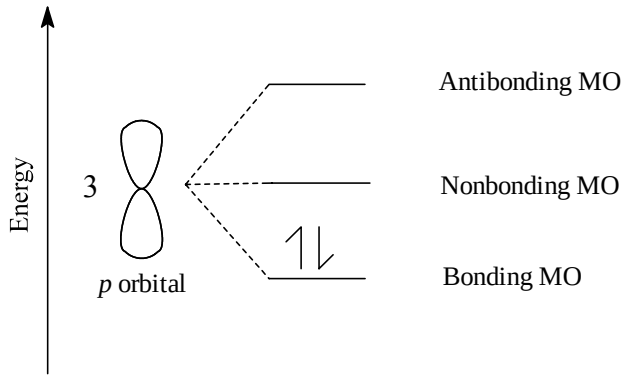


Figure 16.5. The energy relationship between the constituent *p* orbitals and the π MOs of the allyl cation. The antibonding, nonbonding, and bonding MOs are marked.

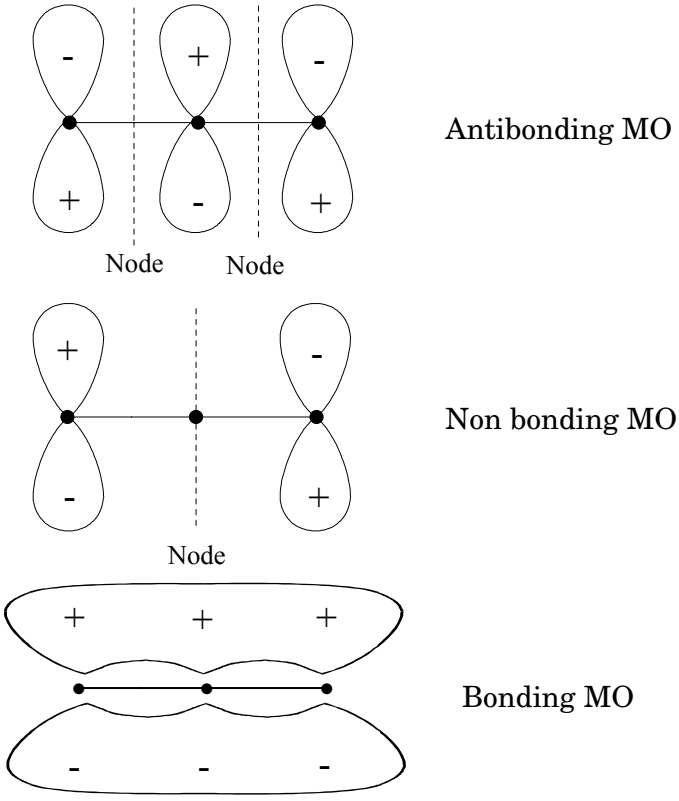


Figure 16.6. The molecular orbitals of an allylic carbocation. The π_1 MO is the bonding MO, the π_2 MO is nonbonding, and the π_3 MO is antibonding.

A nonbonding MO has no bonding or antibonding interactions in the MO. The energy level of a nonbonding MO is the same as the isolated p *orbitals.*

In the allylic carbocation, a pair of electrons fills the π_1 MO making it a bonding MO. The π_2 MO is a **nonbonding molecular orbital** because there is no possible overlap between the *p* orbitals of C1 with either C2 or C3. The node in this orbital coincides with the central carbon in the carbocation. The structure of the π_2 molecular orbital may seem strange, but the node is located in the only symmetrical position for a single node in the molecular orbital. Electrons in this orbital have the same energy as an isolated *p* orbital. Both the nonbonding (π_2) and the antibonding (π_3) MOs are empty. The overlaps in the π_3 MO are all antibonding overlaps.

Exercise 16.3

In strongly acidic solutions, 1,4-cyclohexadiene tautomerizes to 1,3-cyclohexadiene. Propose a mechanism for this reaction. Explain why this reaction is energetically favorable.

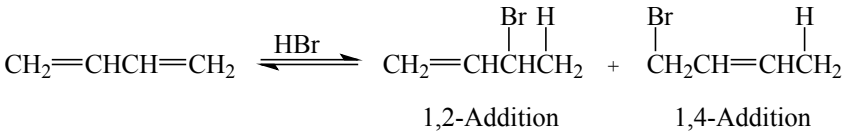
16.4 Conjugate Addition Reactions

This section presents the first of several reactions in which the conjugated diene acts as one functional group instead of two. The reaction covered here is the electrophilic addition reaction of conjugated dienes. Although there are some differences, conjugated dienes undergo electrophilic addition reactions in a way that is similar to unconjugated alkenes.

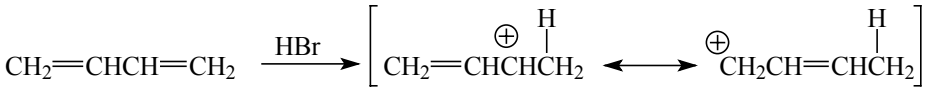
An electrophilic addition reaction with a conjugated diene has two possible pathways. In the reaction of 1,3-butadiene with HBr, for example, one pathway adds the HBr across one of the double bonds. This reaction is called a **1,2-addition** reaction. The second possible pathway adds the HBr to the ends of the diene in a **1,4-addition**, or a **conjugate addition,** reaction.

A 1,2-addition adds reactants to adjacent atoms.

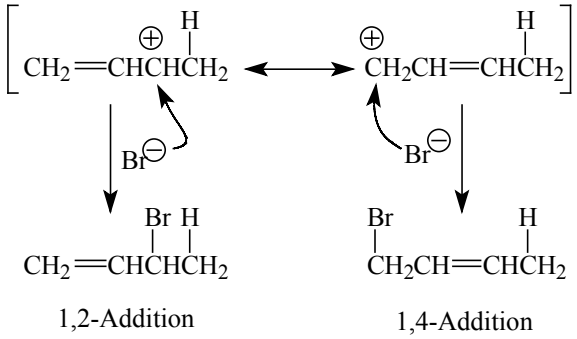
A 1,4-addition adds reactants to atoms 1 and 4 of a conjugated system.



As HBr adds to 1,3-butadiene, the reaction follows a mechanism similar to the one for the addition of HBr to an unconjugated alkene. The reaction proceeds in two steps. In the first step, the proton adds to either end of the conjugated system producing an allylic carbocation.



In the second step, the bromide ion attacks one of the carbon atoms sharing the positive charge in the allylic carbocation.



In this reaction, the carbon where the bromine reacts depends on the temperature of the reaction mixture. Thus, controlling the temperature makes it possible to control the reaction pathway. Table 16.3 summarizes the change in the ratio of 1,2- and 1,4-addition products in the reaction of 1,3-butadiene with HBr according to reaction temperature.

Temperature (°C)	1,2-Addition (%)	1,4-Addition (%)
–78	81	19
25	56	44
45	15	85

Table 16.3. The effect of reaction temperature on the ratio of 1,2- and 1,4-addition to 1,3-butadiene.

The reaction is also reversible. Taking either the 1,2- or the 1,4-addition product (or a mixture of the two), adding a small amount of HBr, and reacting it at a certain temperature produces the same product distribution as you would get by adding HBr to 1,3-butadiene at that same temperature in the first place. For example, the 1,2-addition product, when heated to 45°C in the presence of catalytic amounts of HBr, converts to the same 15:85 product ratio that is obtained when 1,3-butadiene is reacted with HBr at 45°C.

In a thermodynamically controlled reaction, the reaction produces the most stable product.

In a kinetically controlled reaction, the reaction follows the pathway that requires the lowest energy of activation.

The change in the product ratio in the previous reaction of 1,3-butadiene with HBr is an example of what frequently happens with electrophilic addition reactions of conjugated dienes and with some other reactions as well. The **thermodynamic control** of the reaction competes with the **kinetic control** of the reaction. Many organic

reactions are both kinetically controlled and produce the most thermodynamically stable product.

At low temperatures the addition of HBr to 1,3-butadiene is kinetically controlled, but the product obtained is less stable than when the reaction is run at higher temperatures. The reaction profile in Figure 16.7 shows that the activation energy for the 1,2-addition reaction (the kinetically controlled reaction) is lower than the activation energy of the 1,4-addition reaction. However, the 1,4-addition product is more stable than the 1,2-addition product because the double bond in the 1,4-addition product is disubstituted. To form the 1,4-addition product, the temperature of the reaction must be raised. The reaction is then thermodynamically controlled because there is sufficient activation energy to form both products. And, because the reaction is reversible, the two products are in equilibrium with each other with the more stable product in the greater amount.

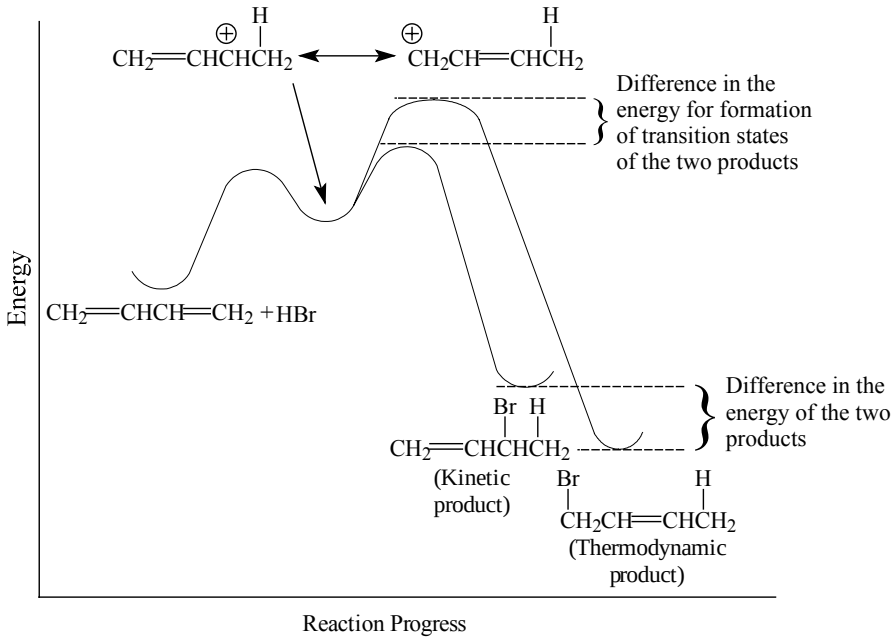


Figure 16.7. Energy diagram showing the relationship between the kinetic and thermodynamic control of the addition of HBr to 1,3-butadiene.

The allylic carbocation also plays a part in the competition between kinetic and thermodynamic control. Of the two resonance contributors, the secondary carbocation is the major contributor due to its greater stability. When the nucleophilic bromide ion attacks, it attacks faster at the secondary carbon than at the primary carbocation. Thus, when the reaction takes place at low temperatures,

the reaction gives a larger ratio of the 1,2-addition product. Because there is insufficient activation energy available for many of the allylic ions to produce the 1,4-addition product, the majority of product is the less stable 1,2-addition product.

Exercise 16.4

When Br_2 is added to 1,3-butadiene at –15°C, two products form, **J** and **K** in a 60:40 ratio. At 60° the ratio is 10:90. Propose structures for **J** and **K**. Justify your choices with a mechanism that accounts for the formation of the two products.

Special Topic—Ultraviolet Spectroscopy

Chapters 9 and 10 discuss infrared spectroscopy, mass spectrometry, and nuclear magnetic resonance spectroscopy. These three spectroscopic techniques provide useful information about functional groups, the carbon—hydrogen framework, and the molecular weight of a molecule. **Ultraviolet (UV) spectroscopy** is a more specialized technique that gives information about conjugated molecules. Because UV spectroscopy is so specialized, organic chemists do not widely use it to characterize compounds. However, when its use is appropriate, it provides valuable information.

Ultraviolet, or UV, spectroscopy examines the π and nonbonding electrons in a molecule.

When a compound absorbs light in the UV region, π electrons and nonbonding electrons conjugated with π MOs are excited from lower electronic levels to higher electronic levels. Because of these transitions in electron energy levels, UV spectra are sometimes called **electronic spectra**.

Electronic spectra examine the transition in energy levels of the electrons in a molecule.

The UV spectrum of 1,3-butadiene shown in Figure 16.8 is a typical UV spectrum. It shows a single broad absorption band centered at a wavelength of 217 nm. The wavelength of maximum absorption is called λ_{max}. Seldom does a UV spectrum show much more detail than is shown in the spectrum of butadiene.

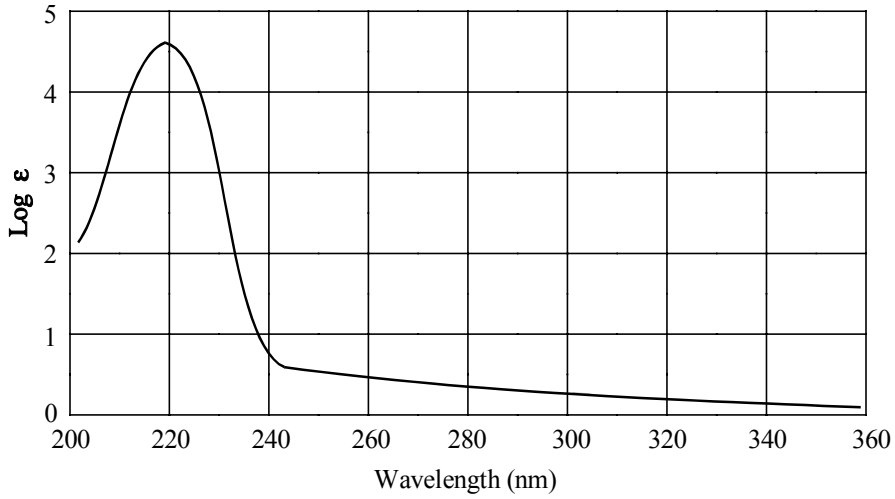


Figure 16.8. The UV spectrum of 1,3-butadiene.

The extinction coefficient is a measure of the amount of UV light absorbed by a sample under a set of standard conditions.

The amount of UV light absorbed by a sample is called the sample's **extinction coefficient**, ε, and is defined by the following equation.

$$\varepsilon = \frac{A}{Cl}$$

In this equation, A is the experimental absorbance value, C is the concentration of the sample in moles/L, and l is the distance in cm the UV light travels through the sample. The extinction coefficient is a constant for the particular substance being measured. Values typically are in the range of 8,000 to 25,000.

When a compound absorbs UV light, an electron is excited from the HOMO to the LUMO. For most conjugated polyenes, the HOMO is a bonding π orbital, and the LUMO is an antibonding π^* orbital. Thus, a $\pi \rightarrow \pi^*$ transition occurs. The energy required depends on the gap between the HOMO and LUMO in the molecule. For nonconjugated alkenes the energy is typically 170-180 nm. For conjugated dienes the gap between the HOMO and LUMO is smaller so the λ_{max} is at wavelengths longer than 215 nm. Increasing the number of double bonds in conjugation decreases the energy between the HOMO and LUMO, and so the λ_{max} occurs at longer wavelengths. 1,3,5-Hexatriene has a λ_{max} of 258 nm, benzene of 254 nm, and 1,3,5,7-octatetraene of 290 nm. Figure 16.9 illustrates the UV spectrum of benzene.

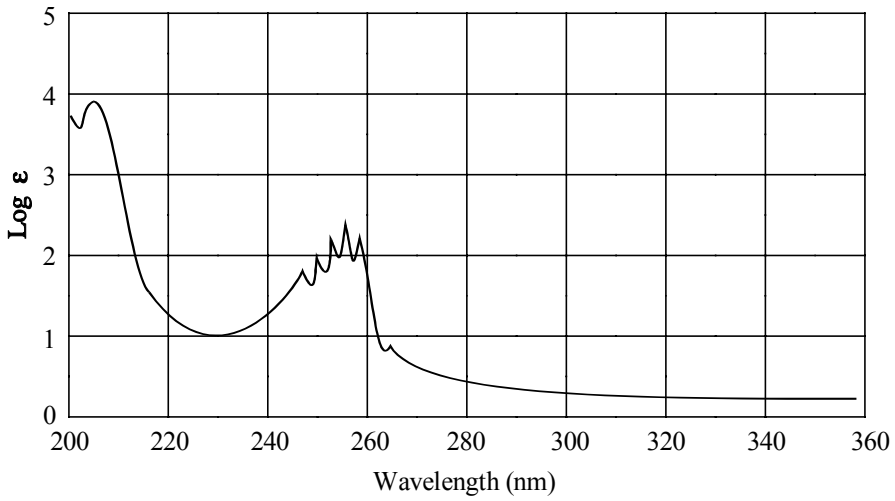
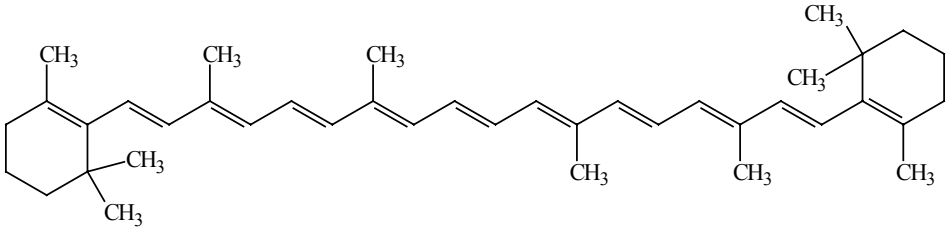


Figure 16.9. The UV spectrum of benzene

Exercise 16.5

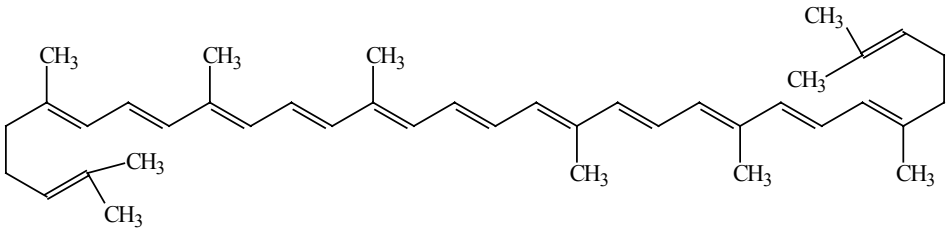
Two compounds **J** and **K** have a molecular formula of C_6H_8. Both react readily with bromine and potassium permanganate. Both also react with hydrogen in the presence of platinum forming cyclohexane. Compound **J** shows no absorption in the UV spectrum above 200 nm, but compound **K** absorbs at 256 nm. Assign structures to **J** and **K**.

Compounds with more than eight conjugated double bonds absorb light in the visible region of the spectrum. These compounds are perceived to have color. For example, β-carotene has 11 conjugated double bonds and absorbs at 497 nm. Light at 497 nm is blue-green in color. You see the complementary color red-orange because the blue-green is strongly absorbed. β-Carotene is responsible for the color of carrots.



β-Carotene

The red color of tomatoes is due to the presence of lycopene. Lycopene also has 11 conjugated double bonds and a λ_{max} of 505 nm. The concentration of lycopene in tomatoes is small. There is less than 25 mg of lycopene in 1 kg of ripe tomatoes.



Lycopene

Exercise 16.6

Alkyl groups on conjugated systems have an effect on the λ_{max} of the molecules. The following UV spectra have been measured.

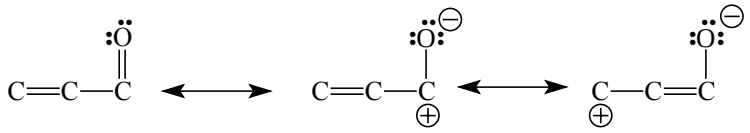
Compound	λ_{max}
1,3-Butadiene	217
2-Methyl-1,3-butadiene	220
1,3-Pentadiene	223
2,3-Dimethyl-1,3-butadiene	226
2,4-Hexadiene	227
2,4-Dimethyl-1,3-pentadiene	232

Calculate the effect of the presence of an alkyl group on the λ_{max} of a molecule. Using your calculations predict the λ_{max} of 2,5-dimethyl-2,4-hexadiene.

16.5 Double Bonds Conjugated with Carbonyl Groups

A α,β-conjugated carbonyl group is an alkene conjugated with a carbonyl group.

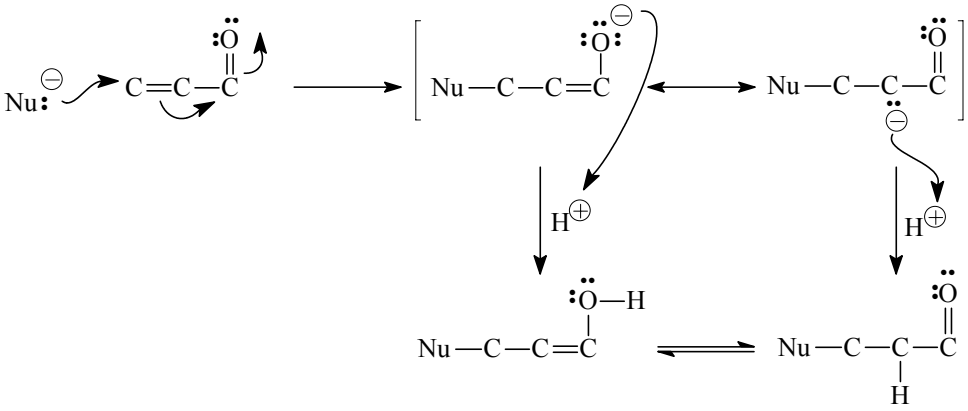
Because the π electrons of carbon—carbon double bonds are available to interact with electrophiles, all alkenes, including unconjugated and conjugated dienes, undergo electrophilic addition reactions. Because the carbon—oxygen double bond is polar, carbonyl group reactions involve nucleophilic additions to the carbon—oxygen double bond. An **α,β-conjugated carbonyl group** also undergoes a nucleophilic addition reaction involving both the carbon—carbon double bond and the carbonyl group. In the case of an α,β-unsaturated carbonyl compound, the electrophilic nature of the carbonyl carbon extends to the β-carbon of the carbon—carbon double bond pulling electron density away from the β carbon leaving it electron deficient. Thus, an alkene, which normally undergoes an electrophilic addition, can now undergo a nucleophilic addition.



Nucleophilic addition reactions of conjugated carbonyl groups are similar to the electrophilic addition reactions of conjugated dienes covered in Section 16.4. As with the conjugated dienes, they undergo both 1,2- and 1,4-additions. With the 1,2-additions, however, the reaction almost always involves the carbonyl group but seldom the double bond portion of the molecule. Because 1,2-additions of conjugated carbonyls follow the same mechanism as discussed in Chapter 7, the rest of this section discusses 1,4-addition reactions.

Another similarity between nucleophilic addition reactions of conjugated carbonyl groups and electrophilic addition reactions of conjugated dienes is that as the 1,4-nucleophilic addition reaction progresses, it follows a two-step mechanism similar to the electrophilic addition reactions. But don't let the similarities get in the way of understanding the differences of these reactions. In the first step, the nucleophile attacks the electron deficient β carbon to form an anion with the nucleophile bonded to the β carbon. As in a nucleophilic addition to a carbonyl group, the oxygen takes up the electron density from the nucleophile giving it a surplus of electrons and a negatively charged **enolate** ion. In step two, because this anion is particularly susceptible to a reaction with the empty orbital of a proton, protonation of the resonance-stabilized anion intermediate occurs to produce a carbonyl group or an enol. The enol then rapidly tautomerizes to a carbonyl group.

An enolate ion is a resonance-stabilized anion where the charge is distributed over a carbonyl carbon and the α carbon.

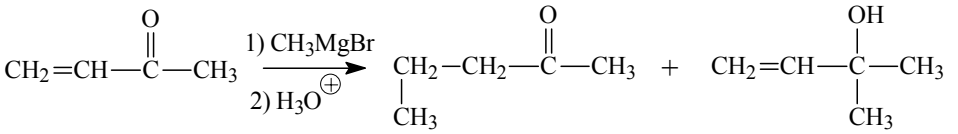


Conjugate addition reactions are 1,4-addition reactions involving conjugated carbonyl substrates.

The Michael addition is discussed further in Section 20.7, page 000.

Carbonyl addition reactions are the subject of Chapter 7.

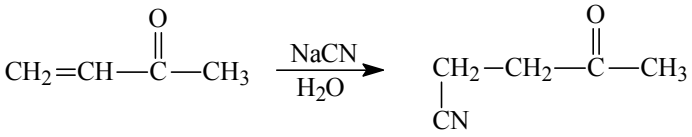
Conjugate addition reactions occur with a variety of nucleophiles and conjugated carbonyl substrates. This reaction is particularly useful with the Michael addition reaction in which a carbanion is the nucleophile. Another example is the Grignard reaction. The Grignard reagent reacts with an α,β-conjugated carbonyl system to produce a mixture of carbonyl addition (1,2) and conjugate addition (1,4) products.



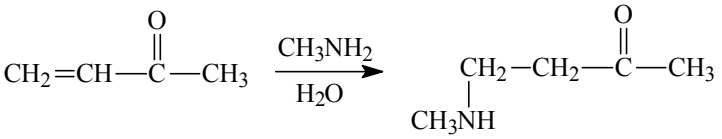
2-Pentanone 72%

2-Methyl-3-buten-2-ol 28%

Other nucleophiles also add to a conjugated carbonyl system. These reactions mostly produce the conjugated addition reaction products.



4-Cyano-2-butanone (97%)



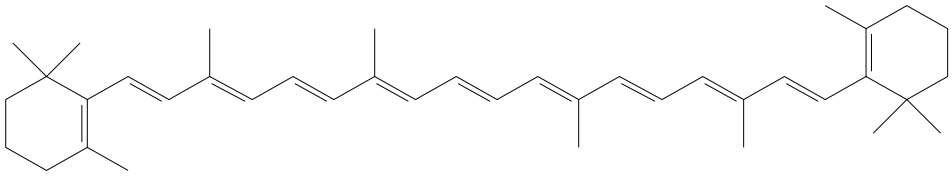
4-Methylamino-2-butanone (98%)

Exercise 16.7

Write a mechanism for the addition of HCl to 3-buten-2-one. Is the product formed the result of a Markovnikov addition or an anti-Markovnikov addition?

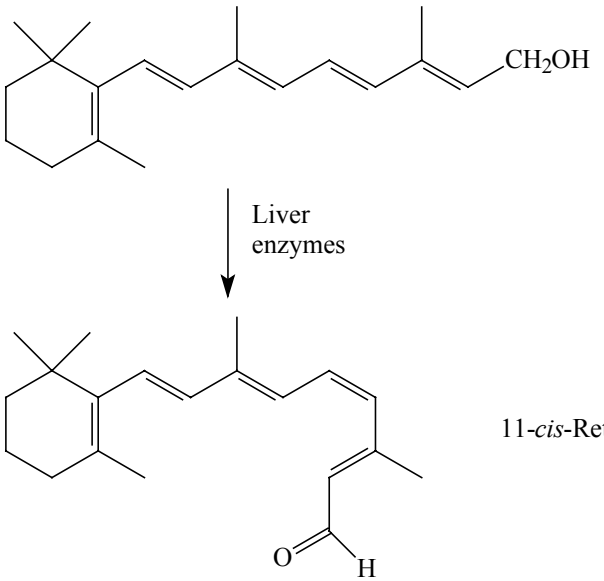
Sidebar—The Chemistry of Vision

What you eat is what you see. At least that's the way it seems with β-carotene. β-Carotene is the yellow-orange pigment responsible for the color of carrots and many other yellow to red plants and is also an important chemical necessary for vision. Many of the chemical compounds that give color to organic substances are extended systems of conjugated double bonds. Systems with two conjugated double bonds absorb in the ultraviolet region of the spectrum. The greater the number of conjugated double bonds contained by the system, however, the longer the wavelength of absorption. As the wavelength of absorption becomes longer it moves into the visible region of the spectrum. β-Carotene has 11 conjugated double bonds.



β-Carotene

β-Carotene is the biological precursor of vitamin A, or retinol. With the aid of enzymes in the liver, the body converts retinol to 11-*cis*-retinal. 11-*cis*-Retinal, in turn, is the key chemical component in vision.



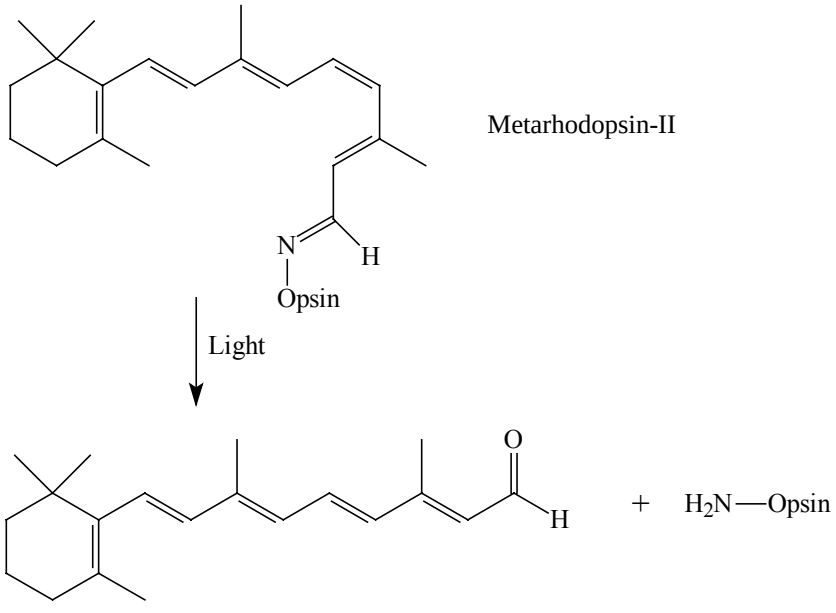
Mammals cannot synthesize vitamin A, yet vitamin A is the essential precursor to 11-*cis*-retinal. So mammals must ingest about 2.7 mg per day of either vitamin A or β-carotene. Mammals can convert β-carotene to vitamin A. Failure to ingest sufficient vitamin A

or β-carotene leads to night blindness. A continued deficiency in vitamin A or β-carotene leads to xerophthalmia, a disease that progresses from night blindness to total blindness.

In the absence of light, 11-*cis*-retinal bonds to a protein called opsin to form rhodopsin. Although neither opsin nor retinal absorb much light in the visible region of the spectrum, rhodopsin has a broad absorption range, covering the visible spectrum. Human rhodopsin has a peak absorption of about 500 nm, so the human eye absorbs green light most efficiently.

The process of seeing color is a cycle of chemical reactions. The cycle begins when light strikes the rhodopsin containing photoreceptors in the eye. The light causes a change in the rhodopsin allowing the eye to perceive an object's color. The eye then reforms rhodopsin; thus, readying itself to see again. In 1957, George Wald and Ruth Hubbard studied this cycle of chemical reactions. They discovered that when light strikes the appropriate photoreceptors, it catalyzes the isomerization of the 11-*cis*-retinal group of rhodopsin to its all *trans* isomer. This isomerization triggers a response in the nerve cells, and the nerve cells transmit that response to the brain. The brain perceives that response as vision.

The all *trans* isomer is 35 kcal/mole more stable than the *cis* isomer. The isomerization of the *cis* double bond to the *trans* isomer takes place in 6 picoseconds (6×10^{-12} seconds) and, within one second, several additional steps take place to form metarhodopsin-II. Metarhodopsin-II dissociates to opsin and *trans*-retinal.



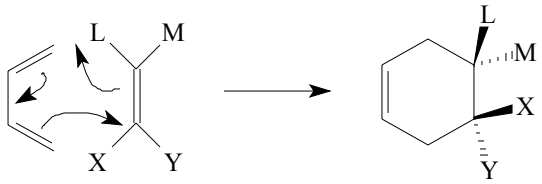
Retinal

In the presence of light, the enzyme *retinal isomerase* converts the *trans*-retinal back to the 11-*cis*-retinal allowing the cycle to repeat. Calcium ions in the cell and the cell membranes control how fast the visual system recovers from exposure to light. The isomerization of 11-*cis*-retinal to the *trans* isomer is the basis of vision in all living creatures regardless of the anatomy of the photoreceptors.

16.6 The Diels-Alder Reaction

Studies of one variety of the conjugate addition reaction type earned the 1950 Nobel Prize in chemistry for Otto Diels and Kurt Alder of the University of Kiel in Germany. Diels and Alder began publishing reports about their work in 1928. The reaction that they investigated, now known as the **Diels-Alder reaction,** adds an alkene to a conjugated diene to form a cyclic alkene. The reaction follows the general mechanism shown below.

The Diels-Alder reaction adds an alkene to a conjugated diene to form a cyclic alkene.

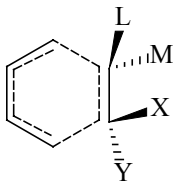


The alkene that reacts with a conjugated diene in the Diels-Alder reaction is called a **dienophile**. Because the Diels-Alder reaction produces a new six-membered ring, it is called a [4+2] **cycloaddition reaction**. The Diels-Alder reaction is one of a series of cycloaddition reactions.

Dienophile means "diene lover." This term refers to an alkene that reacts with a conjugated diene.

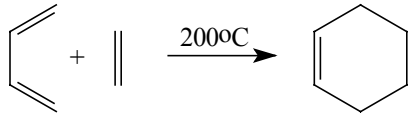
A cycloaddition reaction is an addition reaction that forms a ring. The [4+2] means that a four atom chain reacts with a two atom chain forming the ring.

The Diels-Alder reaction is a concerted reaction in which the diene must achieve the s-*cis* conformation before the reaction occurs. In the reaction's transition state, bonds form that involve both ends of the diene system and both carbons of the dienophile.



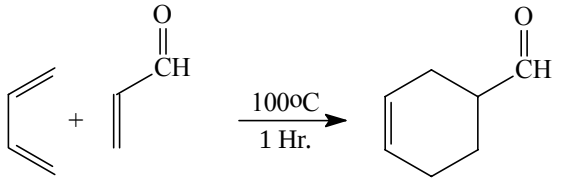
Transition state for the Diels-Alder reaction

The simplest of all Diels-Alder reactions, the reaction of 1,3-butadiene with ethene, proceeds with difficulty. At 200°C, its yield of cyclohexene is only 20%, even after a prolonged reaction time.

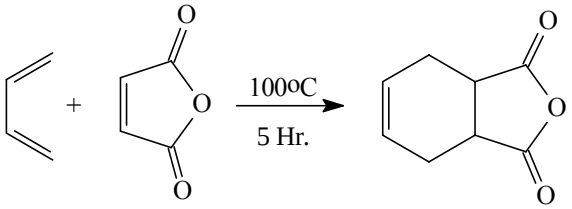


(20%)

However, substituting a dienophile with an electron-withdrawing carbonyl group directly attached to the double bond enhances the reaction's reactivity, and the reaction proceeds more readily.

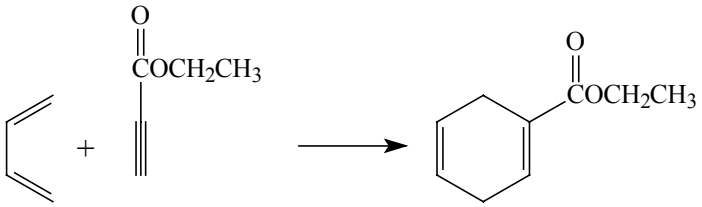


(100%)



(100%)

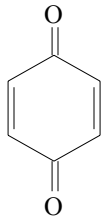
Alkynes also make good dienophiles in the Diels-Alder reaction. But, as with an alkene dienophile, the alkyne dienophile reacts poorly with the diene unless it possesses an electron-withdrawing group bonded to the triple bond.



(84%)

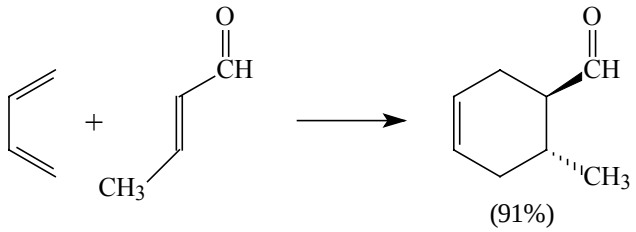
Exercise 16.8

Benzoquinone is a very reactive dienophile. It reacts with 2-chloro-1,3-butadiene to produce a single product in nearly 100% yield. What is the structure of that product?

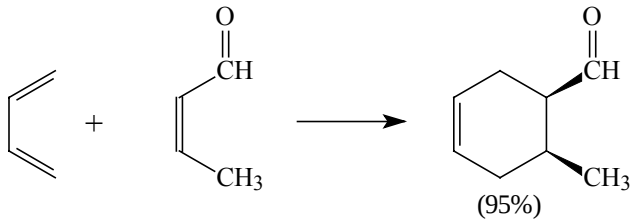


Benzoquinone

The Diels-Alder reaction is stereospecific, because it requires the diene to adopt the s-*cis* conformation before the reaction can take place. The positions of the substituents on the dienophile are in the same relative arrangement in the product. Thus, any substituents on the dieneophile that are *trans* end up *trans* in the product, and the substituents that are *cis* to each other in the dienophile are *cis* in the product. In each of the following reactions, the product shown is the only product that is possible for the reaction.

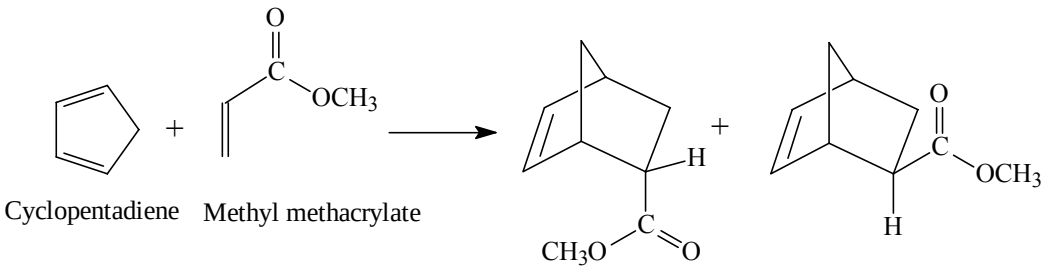


(91%)



(95%)

The Diels-Alder reaction is also stereoselective. The addition of methyl acrylate to cyclopentadiene to form a bicyclic system illustrates this point.



Cyclopentadiene Methyl methacrylate

73% Endo isomer 27% Exo isomer

In the endo isomer, the substituent bonds anti to the bridge not containing the original diene carbons. With the exo isomer, the substituent bonds syn to the bridge not containing the original diene carbons.

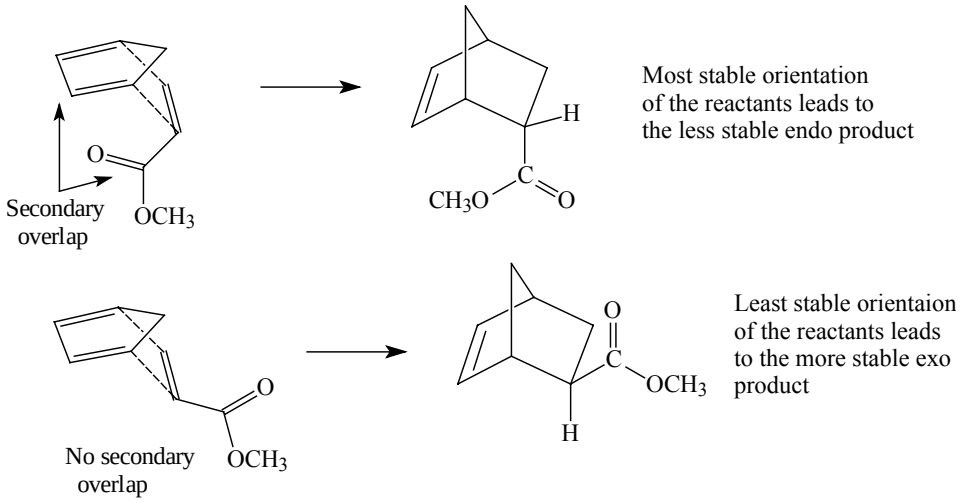
Although the reaction produces both of the two possible products, it forms the **endo** isomer in higher quantities than the **exo** isomer.

This stereoselective preference also shows that the Diels-Alder reaction is kinetically controlled rather than thermodynamically, or equilibrium, controlled. As you may remember from Section 16.3, a kinetically controlled reaction requires the least amount of energy to run, but it may or may not produce the most stable product. A thermodynamically controlled reaction requires more energy to run but always produces the most stable product. Here the endo isomer is less stable, although only slightly so, than the exo isomer but requires less activation energy to form. Thus, the reaction is kinetically controlled.

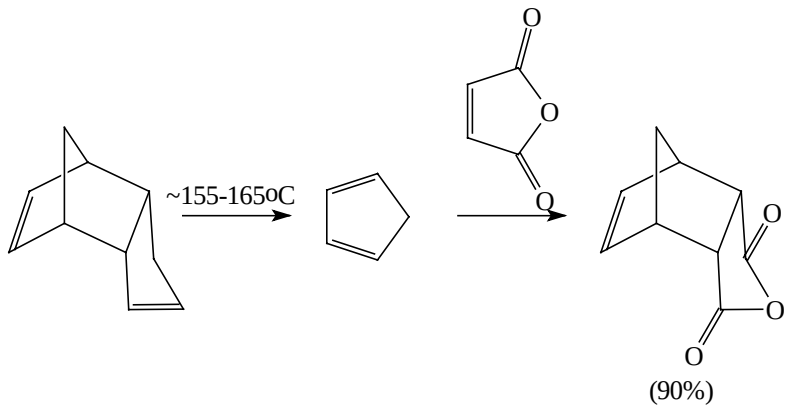
This situation raises a question. If the two products are so close in stability, why does the reaction require more energy to form the more stable isomer? It does so because of the orientation of the electron-withdrawing carbonyl group. In the Diels-Alder reaction, the major product comes from the transition state in which the electron-withdrawing groups orient themselves syn with respect to the diene. The preference for the endo product is called the **endo rule**, or sometimes the **Alder rule**. As the π bonds of the electron-withdrawing group approach the C2 and C3 atoms of the diene unit, the proximity of the electron-withdrawing group to these carbon atoms results in a **secondary overlap** between the orbitals of the carbons and the orbitals of the electron-withdrawing group. A secondary overlap influences the reaction but does not form a bond, whereas a primary overlap forms a bond. In a Diels-Alder reaction, the secondary overlap helps to stabilize the transition state leading to the Diels-Alder product.

The endo, or Alder, rule describes the preference for the endo product in the Diels-Alder reaction.

In a secondary overlap, orbitals interact and share electron density but do not formally create a new bond.



Synthesis of *cis*-Norbornene-5,6-*endo*-dicarboxylic Anhydride



Cyclopentadiene

Place 8 mL (0.053 mol) of dicyclopentadiene in a 50 mL flask. Add a fractional distillation setup and cool the receiver in ice. Heat the dicyclopentadiene to obtain a rapid reflux. The temperature at the top of the fractional distillation column should not exceed 42°C. Collect 6-7 mL of cyclopentadiene in the ice cooled receiver. This requires about 45 minutes. If any moisture condenses in the cyclopentadiene, dry it with 0.5-1.0 g of calcium chloride.

cis-*Norbornene-5,6*-endo-*dicarboxylic anhydride*

Place 6g (0.06 mol) of maleic anhydride in a 125 mL Erlenmeyer flask. Dissolve the anhydride in 16 mL of ethyl acetate, heating if necessary. Add 16 mL of hexane or petroleum ether (60-80°C) and cool in ice. Some anhydride may crystallize. If the cyclopentadiene is cloudy, add 1 g of calcium chloride to remove the moisture. Add 6 mL (0.066 mol) of dry cyclopentadiene to the reaction mixture. Keep the reaction in the ice bath and swirl until the exothermic reaction is over. Heat the mixture on a hot

plate to dissolve the solid. Allow the solution to stand until it reaches room temperature and then cool in ice. Yield of the product is 9.2 g (90%), m.p. 164-165ºC.

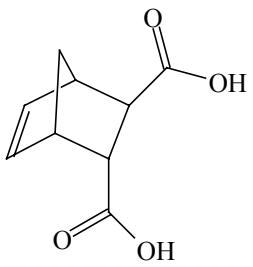
Discussion Questions

1. Write a mechanism for the formation of cyclopentadiene. What type of reaction is it?
2. Why is it necessary for the cyclopentadiene to be dry? Write a mechanism for any reaction that you expect to occur with water present in the reaction mixture.
3. In addition to the main product, two side reactions occur. What structures are formed by these two minor side reactions?

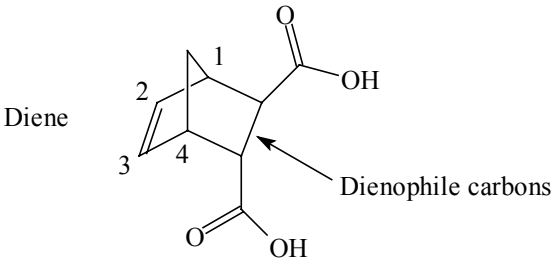
Solved Exercise 16.2

What diene and dienophile will produce the following Diels-Alder products?

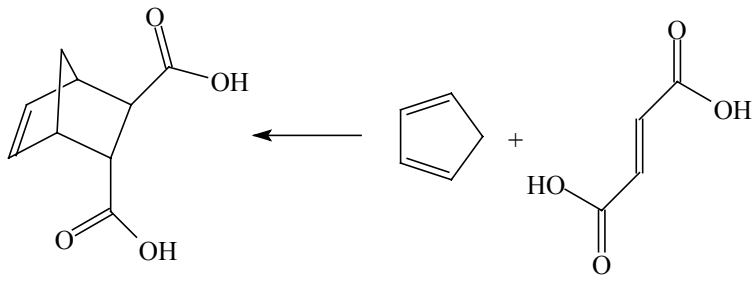
a)



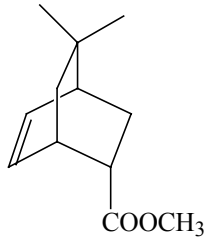
Solution
This molecule divides into its two components, the diene and dienophile as follows:



Because one of the carboxylic acid groups is exo and the other endo, the groups on the dienophile are *trans*. Thus, the reaction is as shown below.

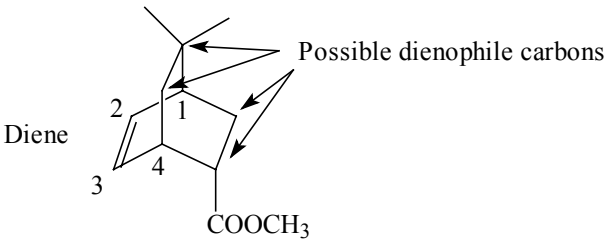


b)

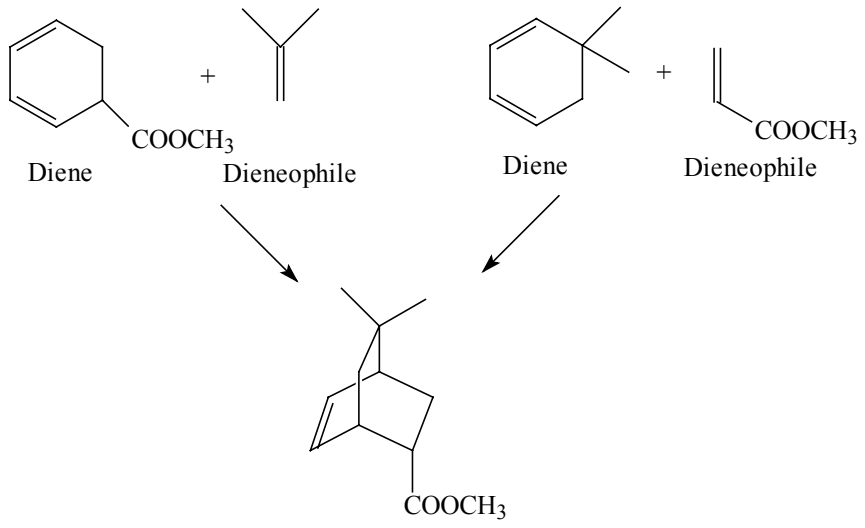


Solution

Two possible combinations of reactants could produce this product.



The possible combinations of starting materials are shown below.

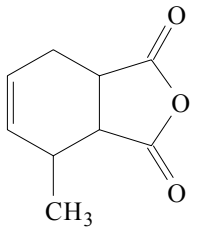


In principle, either combination of diene and dienophile could serve as starting materials in a Diels-Alder reaction. Recall, however, that dienophiles with electron-withdrawing groups react much faster and generally produce a higher yield of product than those without such groups. Thus, the pair of reactants on the right would produce the product in better yield.

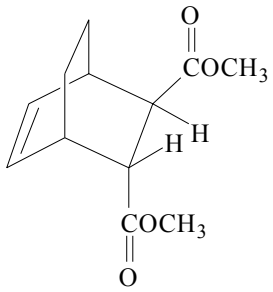
Exercise 16.9

What combination of dienes and dienophiles are required to prepare the following compounds?

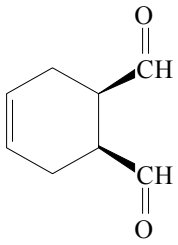
a)



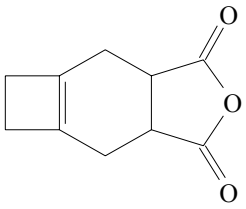
b)



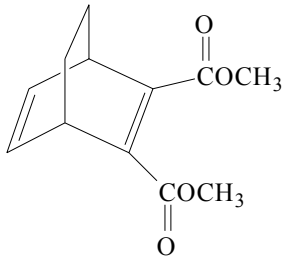
c)



d)

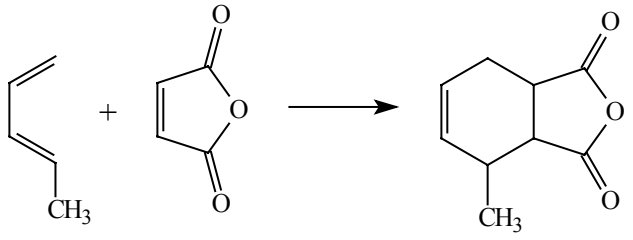


e)



Sample solution

a)



16.7 Orbital Symmetry and the Diels-Alder Reaction

The conservation of orbital symmetry states that the MOs of the reactants flow smoothly into the MOs of the products.

Frontier orbitals are those orbitals that contain the highest energy electrons and the lowest energy unoccupied orbital.

For many years, electrocyclic reactions, such as those that occur with the Diels-Alder reactions, were poorly understood and the outcome was unpredictable. Then, in the mid-1960s, Robert B. Woodward of Harvard University and Roald Hoffman of Cornell University developed a theory that predicts the results of electrocyclic reactions by considering the symmetry of the orbitals of the reactants and the products. This theory, called **the conservation of orbital symmetry**, states that the MOs of the reactants must flow smoothly into the MOs of the products without any drastic changes in symmetry. About the same time, Kenichi Fukui of Kyoto University in Japan also developed a technique for understanding the mechanism of electrocyclic reactions. His technique uses **frontier orbital** analysis. Frontier orbital analysis looks at reactions between the highest energy occupied orbitals and lowest energy unoccupied orbitals. Fukui and Hoffman received the Nobel Prize in chemistry in 1981 for their work.

Knowing what happens in the frontier orbitals of the conjugated diene and the dienophile helps you to understand the mechanism of a Diels-Alder reaction. Keep in mind, even though you are reading about "steps" in the reaction, that the Diels-Alder reaction is a concerted reaction and all bond breaking and bond making occurs simultaneously. As the reaction takes place, the highest energy electrons leave the highest occupied molecular orbital (HOMO) of the conjugated diene because that is the orbital most likely to give up its electrons. These electrons then flow to the lowest unoccupied molecular orbital (LUMO) of the dienophile because the lowest unoccupied molecular orbital is the one most able to accept the electrons from the HOMO. This reaction is called a **symmetry-allowed reaction**. Figure 16.10 shows the orbitals involved in the Diels-Alder reaction.

In a symmetry-allowed reaction, a concerted reaction takes place resulting in a constructive overlap between the reacting orbitals.

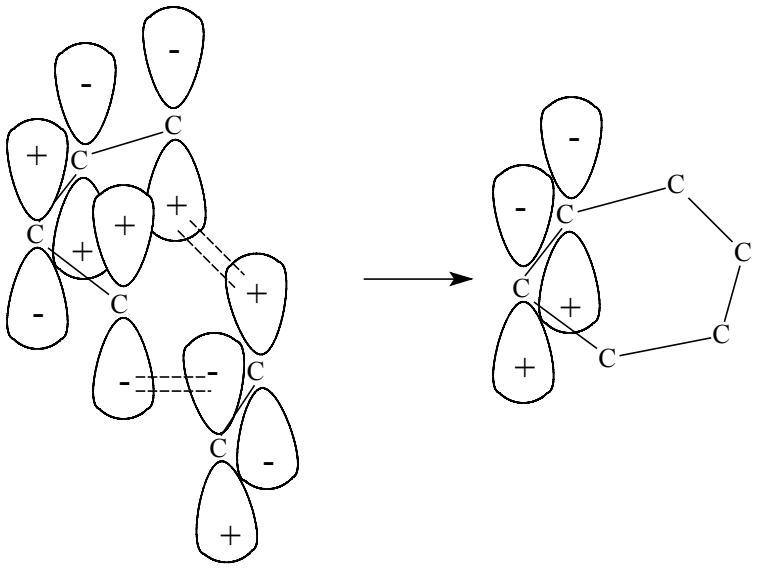
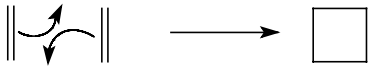


Figure 16.10. The orbital picture of the concerted Diels-Alder reaction mechanism. The HOMO π molecular orbital of the conjugated diene reacts with the π* LUMO of the dienophile.

The most reactive dienophiles have electron-withdrawing substituents. These substituents include carbonyl groups, NO_2, CN, or even another double or triple bond. The electron-withdrawing groups give the double bond of the dieneophile a lower electron density. This lower electron density encourages the flow of electrons from the HOMO of the diene to the LUMO of the dienophile.

A reaction that contrasts with the Diels-Alder reaction is the cycloaddition of two alkenes to form a cyclobutane derivative. This reaction is called a [2+2] cycloaddition reaction. Although the [2+2] cycloaddition reaction looks similar to a Diels-Alder reaction, it is significantly different.



Unlike the Diels-Alder reaction, the [2+2] cycloaddition reaction rarely occurs, and more importantly, it does not proceed via a concerted mechanism. Instead, it appears to follow a stepwise reaction mechanism.

Frontier orbital analysis shows why the thermal [2+2] reaction cannot proceed via a concerted electrocyclic mechanism. Figure 16.11 shows the interaction of the HOMO of one alkene and the LUMO of the other alkene. Notice that two of the electrons that must bond to each other experience an antibonding interaction during the cycloaddition process.

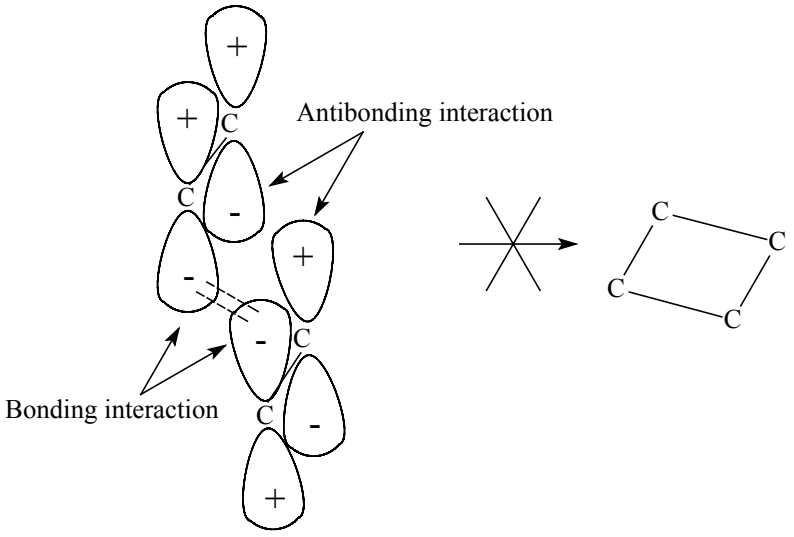


Figure 16.11. The HOMO of one ethylene molecule and the LUMO of another ethylene molecule do not have the proper orbital symmetry to permit two bonds to form in a concerted reaction.

This antibonding interaction raises the energy level of the transition state. Thus, a [2+2] cycloaddition reaction, if it does occur, takes place slowly and via a mechanism in which the two new σ bonds form in separate steps. A cycloaddition reaction that does not allow the two bonds to form in one concerted step is called a **symmetry-forbidden** reaction.

A symmetry-forbidden reaction does not allow a concerted reaction to occur because the reaction would form a destructive overlap between the reacting orbitals.

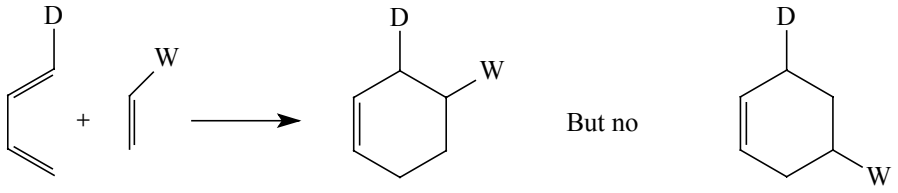
The application of frontier orbital analysis methods to electrocyclic reactions represents one part of what chemists call the Woodward-Hoffman rules. These rules make it possible to analyze many types of organic reactions, but this analysis is beyond the scope of this book.

16.8 Synthesis with the Diels-Alder Reaction

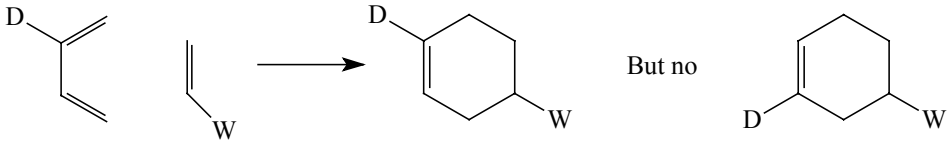
So far this chapter has discussed only symmetrical dienes and monosubstituted or symmetrical dienophiles as the reactants in the Diels-Alder reactions. When looking at these reactants, you would expect the reactions to form only one product, and indeed they do. However, in some cases, even when the diene and dienophile are both unsymmetrically substituted, and you would expect more than one product, the Diels-Alder reaction still gives only a single product.

Not only do Diels-Alder reactions with both diene and dienophile unsymmetrically substituted give a single product, but they do so in very predictable ways. As before, the dienophile works best

with an electron-withdrawing group attached. This group is labeled W in the following drawings. The diene needs a strong electron-donating group attached, and that group is labeled D. Because the donating group of the diene aligns itself with the electron-withdrawing group of the dienophile, the specific product that each reaction forms depends on the location of the electron-donating group. If the donating group is attached to C1 of the diene, the product forms with D and W in the 3 and 4 positions of the ring.

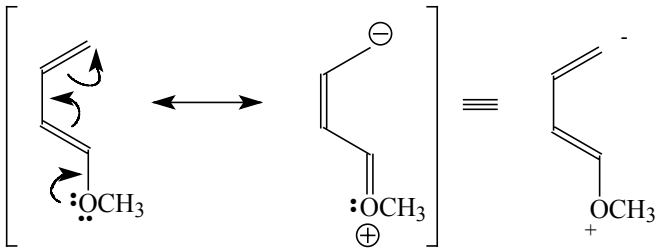


If the donating group is attached to C2 of the diene, the product forms with D and W in the 1 and 4 positions of the ring.



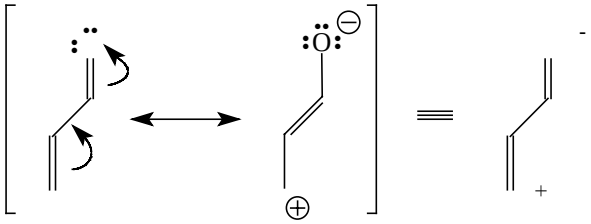
In neither case does the reaction produce the 3,5 (or 2,4) product, even though the 1,3 (or 2,4) product, at first glance, looks feasible.

Looking more closely at what happens with the reactant molecules will help you understand why they orient themselves the way they do for a Diels-Alder reaction. Consider the reaction of 1-methoxy-1,3-butadiene as it reacts with propenal. The methoxy group donates electron density to the diene to produce the following resonance hybrid. The molecule is thus polarized with a partial positive charge on the oxygen and a partial negative on C4.



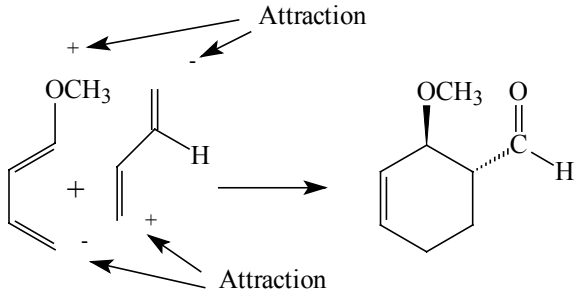
Resonance in 1-methoxy-1,3-butadiene

Propenal also has some polarization because of the following resonance.



Resonance in propenal

When the two react, the positive end of the dienophile aligns itself with the negative end of the diene, and the positive end of the diene aligns itself with the negative end of the dienophile. This alignment produces the lowest energy transition state; and thus, the product has the methoxy group and the aldehyde adjacent to each other.



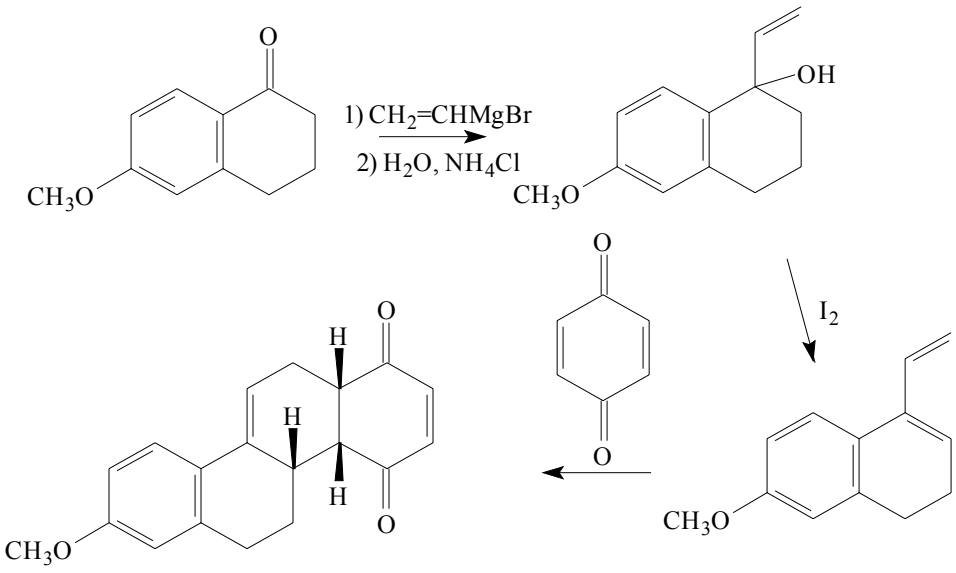
In cases where the diene has a weak electron-donating group, the reaction shows much less preference for the structure of the product that it forms. Although a strong electron-donating group, such as an alkoxy group, orients the Diels-Alder transition state towards forming the 1,2 or 1,4 structure, a weak electron-donating group, such as an alkyl group, may form a product with a 1,3 relationship between the groups. The selectivity for these orientations depends on the strength of the electron donation of the groups bonded to the diene. Similar statements can be made about the electron-withdrawing group of the dienophile. The stronger the group the more the selectivity for the 1,2 or 1,4 structure.

Exercise 16.10

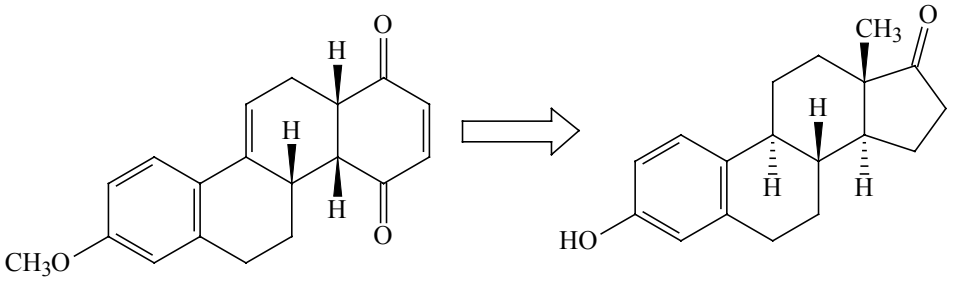
Analyze the reaction of 2-methoxy-1,3-butadiene with propenal. Write a mechanism to explain the 1,4 orientation of the substituents.

Many organic syntheses include the use of some clever Diels-Alder reactions. An example is the synthesis of estrone, a member of the estrogen sex hormones, done by W. S. Johnson and his research

group (*Proc. Chem. Soc.*, 114 (1958); *J. Chem. Soc.*, 244 (1962)). Johnson's work was one of the first complete syntheses that achieved the desired stereoselectivity in the sequence. The reaction begins with several steps that lead to the Diels-Alder reaction.



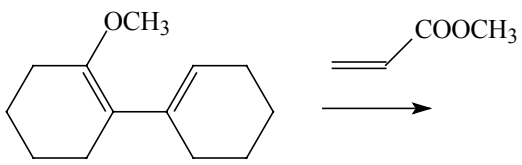
After this intermediate product, the reaction continues through many more steps until it reaches the final product estrone.



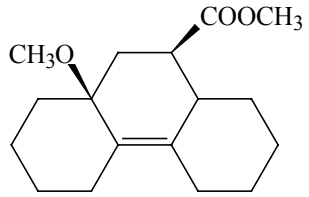
Estrone

Solved Exercise 16.3

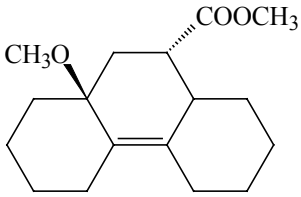
What is the product of the following reaction?



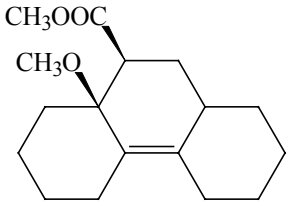
Solution
Four possible products could arise from the proposed reaction and each of these four products also has an enantiomer.



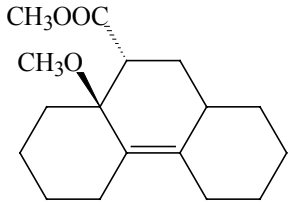
1



2



3



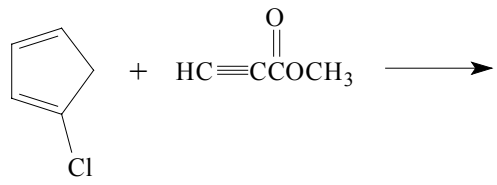
4

The partial positive charge of the methoxy oxygen is attracted to the partial negative charge of the carbonyl oxygen. Thus, products **1** and **2** are produced only in small yield, if at all. Product **4** follows the endo rule and is the major product.

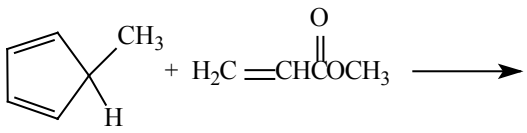
Exercise 16.11

Predict the major products for each of the following reactions. Show the stereochemistry involved where appropriate.

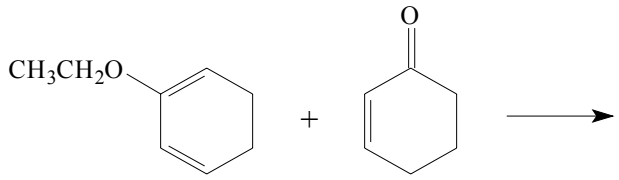
a)



b)

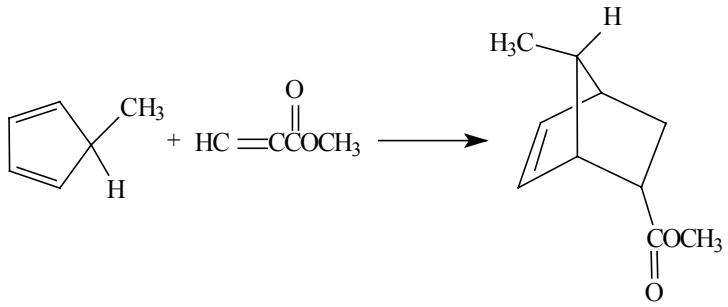


c)



Sample Solution

b)



Key Ideas from Chapter 16

- A conjugated diene is a compound that contains two double bonds separated by a single bond.
- A molecule with a conjugated double bond is more stable than a molecule with the same number of non-conjugated double bonds.
- Conjugated double bonds often act as if they are part of one functional group because all the *p* orbitals involved in the double bonds overlap to form one set of π molecular orbitals. The number of π MOs is equal to the initial number of *p* orbitals.
- A carbocation with the positive charge adjacent to a double bond is called an allylic carbocation. An allylic carbocation is a resonance-stabilized carbocation.
- Dienes undergo both 1,2- and 1,4-addition (conjugate addition) reactions.
- Reactions are either kinetically or thermodynamically controlled. Kinetically controlled reactions follow the lowest energy pathway from substrate to product. Thermodynamically

controlled reactions produce the lowest energy, or most stable, product.

- ❑ The 1,2-addition reaction with a conjugated diene is a kinetically controlled reaction.

- ❑ The 1,4-addition reaction with a conjugated diene is a thermodynamically controlled reaction.

- ❑ 1,4-Addition reactions also take place with α,β-unsaturated carbonyl compounds. These reactions are called Michael additions. In a Michael addition, the electrophile bonds to the carbonyl oxygen, and the nucleophile bonds to the β carbon of the double bond.

- ❑ A Diels-Alder reaction forms a six-membered ring via conjugate addition. Diels-Alder reactions fit into a group of reactions called cycloaddition reactions or electrocyclic reactions. Its formal name is a [4+2] cycloaddition reaction.

- ❑ The Diels-Alder reaction involves a molecule containing a conjugated diene (the diene) and another molecule containing a double bond (the dienophile).

- ❑ The Diels-Alder reaction proceeds best with an electron-withdrawing group on the dienophile.

- ❑ The Diels-Alder reaction is both a stereospecific syn addition reaction and stereoselective. It is stereospecific because any groups attached to the diene and dienophile retain their configuration in the product. It is stereoselective because the relationships between the groups on the diene and dienophile have a preferred orientation.

- ❑ The highest occupied molecular orbital (HOMO) of the diene reacts with the lowest unoccupied molecular orbital (LUMO) of the dienophile in the Diels-Alder reaction. These orbitals are called the frontier orbitals.

- ❑ The proper overlap for bond formation in the Diels-Alder reaction requires an interaction between the HOMO and LUMO of the reactants. This is a symmetry-allowed reaction.

- ❑ The groups attached to the diene and dienophile usually bond in either a 1,2 or a 1,4 relationship on the product. A weak electron-donating group on the dienophile allows the formation

of the 1,3 relationship following the thermodynamically controlled pathway.