CHAPTER

6

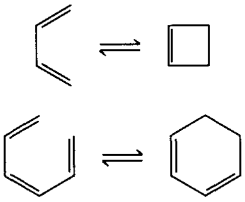
Pericyclic Reactions

I. INTRODUCTION

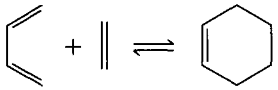
Many reactions involve a cyclic transition state. Of these, some involve radical or ionic intermediates and proceed by stepwise mechanisms. *Pericyclic* reactions are *concerted*, and in the transition state the redistribution of electrons occurs in a single continuous process. In this chapter, we will consider several different types of pericyclic reactions, including electrocyclic transformations, cycloadditions, sigmatropic rearrangements, and the ene reaction.

A. Types of Pericyclic Reactions

- **Electrocyclic transformations** involve intramolecular formation of a ring by bond formation at the ends of a conjugated π system. The product has one more σ bond and one less π bond than the starting material. The reverse reaction, ring opening of a cyclic polyene, is also an electrocyclic process.

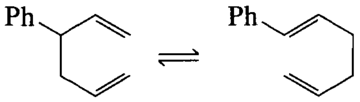


- **Cycloadditions** involve bonding between the termini of two π systems to produce a new ring. The product has two more σ bonds and two less π bonds than the reactants. Common examples are the Diels–Alder reaction and many 1,3-dipolar cycloadditions.



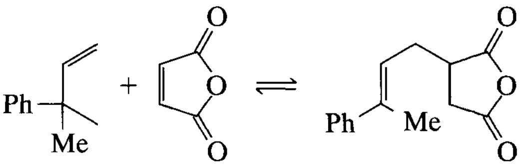
Diels–Alder reaction

- **Sigmatropic reactions.** In these, an allylic σ bond at one end of a π system appears to migrate to the other end of the π system. The π bonds change position, but the total number of σ and π bonds is the same, as in the Cope and Claison rearrangements.



Cope rearrangement

- **Ene reactions.** These combine aspects of cycloadditions and sigmatropic reactions. They may be inter- or intramolecular.



B. Theories of Pericyclic Reactions

Pericyclic reactions can be initiated either thermally or photochemically, but in either case they show great stereospecificity. The conditions under which pericyclic reactions occur and the stereochemistry of the products formed are dependent on the symmetry characteristics of the *molecular orbitals* involved. On this basis, pericyclic processes are classified as either *symmetry-allowed* or *symmetry-forbidden*. There are several theoretical approaches for deriving the *selection rules* governing concerted pericyclic reactions, and each of these theories represents the work of many contributors. All of these approaches assume that a cyclic transition state is formed by π orbital overlap.

- **Conservation of Orbital Symmetry.** This approach relies on a detailed analysis of the symmetry properties of the molecular orbitals of starting materials and products. Orbital correlation diagrams link the orbital characteristics of starting materials and products.
- **Frontier Orbital Theory.** This view focuses on the symmetry characteristics of the highest occupied and lowest unoccupied orbitals, particularly the symmetry at the termini of the systems.
- **Moebius–Huckel Theory.** The molecular orbital array of the transition state is analyzed in terms of aromaticity, which is determined by the number of π electrons.

Each of these theoretical approaches leads to the same predictions regarding reaction conditions and stereochemistry. For a wide range of reactions, *the selection rules can be used empirically, based on a simple method of electron counting, without regard to their theoretical basis*. The selection rules for pericyclic reactions relate three features:

1. The number of π electrons involved.
2. The method of activation.
3. The stereochemistry.

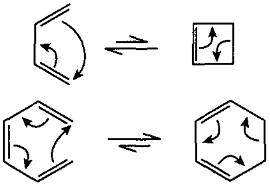
If any two of these features are specified, the third feature is determined by the selection rules.

Note: Reactions involving a cyclic transition state are not always concerted, and the selection rules and their stereochemical consequences apply only to *concerted* pericyclic processes. Indeed, *failure to conform to the selection rules is usually taken as proof that a reaction does not proceed by a concerted mechanism*. On the other hand, failure to react may simply mean that the reaction is symmetry-allowed, but does not occur because the thermodynamics is unfavorable. This point will be discussed further in the next section.

The following sections present an empirical approach to applying the selection rules. The chapter continues with a basic introduction to the analysis of symmetry properties of orbitals and the application of orbital correlation diagrams to the relatively simply cyclobutene-butadiene interconversion; it concludes with some examples of the frontier orbital approach to pericyclic reactions.

2. ELECTROCYCLIC REACTIONS

Electrocyclic reactions are intramolecular ring openings or ring closures. The interconversion of substituted cyclobutenes and butadienes under different conditions illustrates which modes of reaction are symmetry-allowed and the stereochemical consequences of the selection rules. (In the reactions that follow, because there are no polar substituents, the directions of electron flow are arbitrary.) By the principle of microscopic reversibility, the bonding changes involved in going from starting material to product are the exact reverse of the changes involved in going from product to starting material. Thus, for electrocyclic reactions, any analysis we make for cyclization also applies for the ring-opening reaction and vice versa.



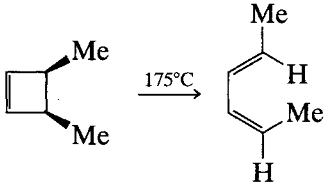
Whereas, in theory, symmetry-allowed electrocyclic reactions may proceed in either direction, in practice one side of the equation is usually favored over the other. Because of the large strain energy of the four-membered ring, the equilibrium for the thermal opening of cyclobutene rings is usually favored over the reverse reaction (ring closure). On the other hand, equilibrium usually favors the six-membered ring rather than the ring-opened compound.

A. Selection Rules for Electrocyclic Reactions

Like other pericyclic reactions, electrocyclic reactions may be initiated either thermally or photochemically. The selection rules enable us to correlate the stereochemical relationship of the starting materials and products with the method of activation required for the reaction and the number of π electrons in the reacting system.

Hint 6.1 To apply the selection rules for electrocyclic reactions, count the number of π electrons in the open-chain polyene.

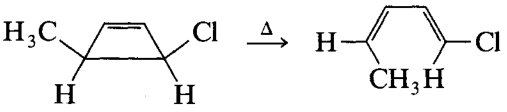
Example 6.1. ***Ring opening of cis-3,4-dimethylcyclobutene.***



The cyclobutene–butadiene interconversion involves four π electrons and is designated a π^4 process. Note that by the principle of microscopic reversibility, the number of π electrons involved in the transformation is the same for ring opening as for ring closing. Once we know the number of π electrons involved in an electrocyclic reaction and the method of activation, the stereochemistry of the process is fixed according to the rules outlined in Table 6.1.

B. Stereochemistry of Electrocyclic Reactions (Conrotatory and Disrotatory Processes)

Example 6.2. ***The thermal ring opening of cis-3-chloro-4-methyl-cyclobutene, a conrotatory process.***



6-1 **6-2**

By applying Hint 6.1, we see that the number of π electrons involved in the transformation is four. The reaction takes place thermally, so that the selection rules as outlined in Table 6.1 indicate that a conrotatory process should occur. The following discussion will show what this means.

TABLE 6.1 Selection Rules for Electrocyclic Reactions

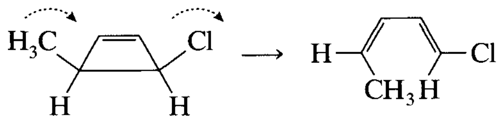
Number of electrons	*Mode of activation*	*Allowed stereochemistry*[a]
$4n$	Thermal	Conrotatory
	Photochemical	Disrotatory
$4n + 2$	Thermal	Disrotatory
	Photochemical	Conrotatory

[a] The terms *conrotatory* and *disrotatory* are explained in Section 6.B.

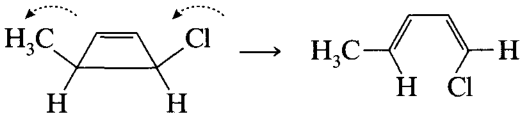
When the cyclobutene ring is transformed into a butadiene, the C-3—C-4 bond breaks. As it does so, there is rotation about the C-1—C-4 bond and the C-2—C-3 bond, so that the substituents on the breaking C-3—C-4 σ bond rotate into the plane of the conjugated diene system of the product. In the starting cyclobutene, the methyl and chloro groups lie above the plane of the four ring carbons; in the product, these groups lie in the same plane as the four carbon atoms of the butadiene. If all possible rotations about the C-3—C-4 σ bond were allowed, four different products would be formed, two by conrotatory processes and two by disrotatory processes. We will take a closer look at this process.

Conrotatory Process

In a conrotatory process, the substituents on C-3 and C-4 rotate *in the same direction.*



6-2



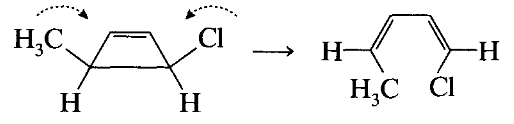
6-3

Clockwise rotation of both substituents gives product **6-2**, whereas *counterclockwise* rotation gives product **6-3**. (The arrows in the figure show the direction of rotation, not the movement of electrons.)

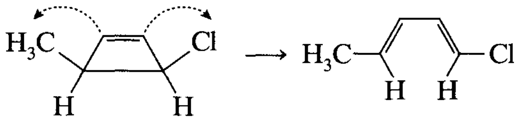
The selection rules predict that the thermal ring opening should be conrotatory for *cis*-3-chloro-4-methylcyclobutene, but they do not distinguish between products **6-2** and **6-3**. Both products are allowed by the selection rules, but experimentally only product **6-2** is formed. An explanation for this preference of one allowed process over the other is beyond the scope of this book; however, possible explanations can be found in the following references: Dolbier, W. R., Jr.; Koroniak, H.; Burton, D. J.; Bailey, A. R.; Shaw, G. S.; Hansen, S. W. *J. Am. Chem. Soc.* **1984**, *106*, 1871–1872; Rondan, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1985**, *107*, 2099–2111; Krimse, W.; Rondan, N. G.; Houk, K. H. *J. Am. Chem. Soc.* **1984**, *106*, 7989–7991.

Disrotatory Process

In a disrotatory process, the substituents on C-3 and C-4 rotate *in opposite directions*.



6-4



6-5

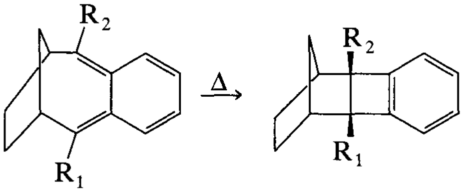
Rotation of the substituents *toward one another* would give the product **6-4**, whereas rotation of the substituents *away from one another* would give the product **6-5**. For the thermal reaction, neither of these rotations is allowed by the selection rules.

To summarize the results in the preceding example: Each of the four rotational modes of ring opening leads to a particular stereoisomer of the product. For the concerted ring opening of a π^4 system, only the two conrotatory modes are allowed. Of these, only one is observed experimentally.

PROBLEM 6.1

By applying Hint 6.1 and the rules in Table 6.1, decide whether the following *thermal* reactions are symmetry-allowed or symmetry-forbidden.

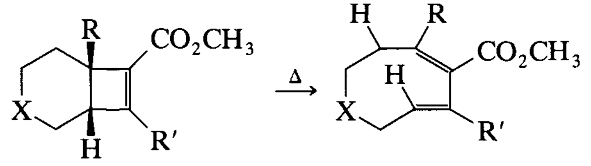
a.



Spellmeyer, D. C.; Houk, K. N.; Rondan, N. G.; Miller, R. D.; Franz, L.; Fickes, G. N. *J. Am. Chem. Soc.* **1989**, *111*, 5356–5367.

PROBLEM 6.1
continued

b.



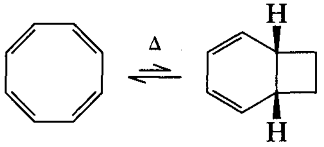
$X = (CH_2)_3$

Vos, G. J. M.; Reinhoudt, D. N.; Benders, P. H.; Harkema, S.; Van Hummel, G. J. *J. Chem. Soc., Chem. Commun.* **1985**, 661–662.

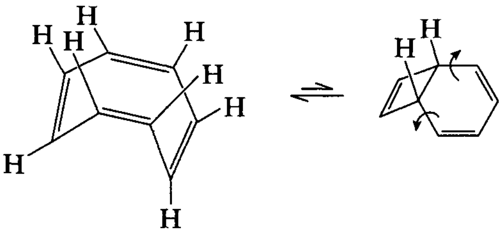
Hint 6.2

When applying the selection rules, only those π electrons taking part in the cyclization are counted.

Example 6.3. *The thermal cyclization of cyclooctatetraene to bicyclo[4.2.0]-octatriene.*



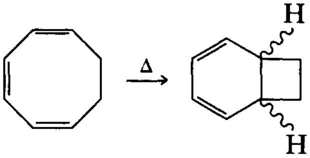
Because the cyclic transition state of the electrocyclic reaction involves joining the ends of the π system, this reaction may be regarded as a π^4 ring closure to a cyclobutene or a π^6 ring closure to a cyclohexadiene. Under thermal conditions, the selection rules require a conrotatory ring closure for the π^4 system, leading to a *trans* ring junction, which is unlikely for such a fusion because of ring strain. On the other hand, the π^6 system should close by a disrotatory process to give a *cis* ring junction. The product observed experimentally is consistent with a disrotatory closure of the π^6 system. Cyclooctatetraene is tub-shaped rather than planar, and the disrotatory process can be visualized as shown in the following drawing:



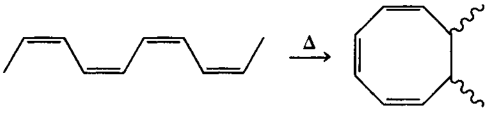
In practice, cyclooctatetraene is the more stable isomer, and the presence of the bicyclic compound has been demonstrated only through trapping experiments.

What is the relative stereochemistry of the ambiguous groups in the following concerted processes? **PROBLEM 6.2**

a.

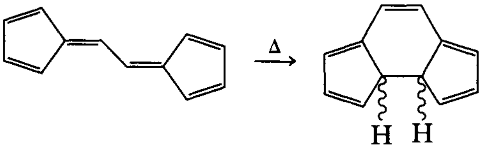


b.



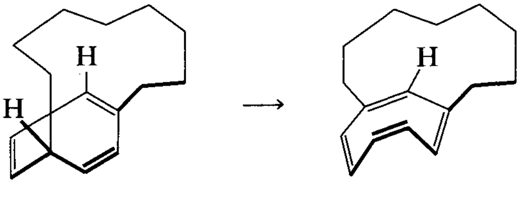
Huisgen, R.; Dahmen, A.; Huber, H. *J. Am. Chem. Soc.* **1967**, *89*, 7130–7131.

c.



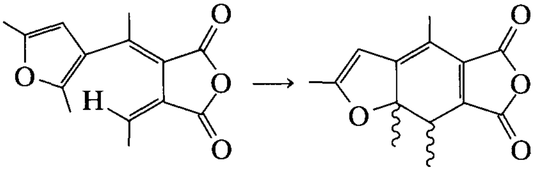
Sauter, H.; Gallenkamp, B.; Prinzbach, H. *Chem. Ber.* **1977**, *110*, 1382–1402.

PROBLEM 6.3 **Is the following reaction symmetry-allowed or symmetry-forbidden? Explain.**



Paquette, L. A.; Want, T.-Z. *J. Am. Chem. Soc.* **1988**, *110*, 3663–3665.

PROBLEM 6.4 **Consider the following concerted process:**



Darcy, P. J.; Heller, H. G.; Strydon, P. J.; Whitall, J. *J. Chem. Soc., Perkin Trans. I*, **1981**, 202–205.

a. What is the relative stereochemistry of the product formed when the reaction is initiated by heat?

b. What is the relative stereochemistry of the product formed when the reaction is initiated by light?

c. What is the relative stereochemistry of the product of the photochemical ring opening of the product formed in part a?

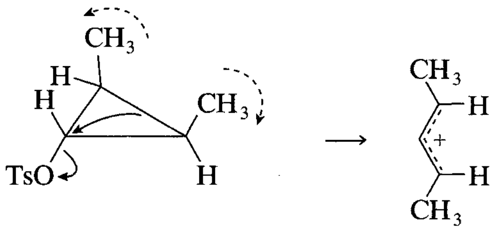
C. Electrocyclic Reactions of Charged Species (Cyclopropyl Cations)

The selection rules can be applied to charged species as well as to neutral molecules. The only requirement is that the reaction be a concerted process involving electrons in overlapping *p* orbitals. For example, the conversion of a cyclopropyl cation to the allyl cation can be considered as a π^2-electrocyclic process. For this process, the selection rules predict a disrotatory process.

Example 6.4. ***The solvolysis of cyclopropyl tosylates.***

The relative rates of concerted ring opening for substituted cyclopropyl tosylates can be explained on the basis of the selection rules and the principle of maximum orbital overlap. The relative rates of solvolysis for two different dimethylcyclopropyl tosylates are shown in the accompanying diagram:

Rel. rate in
HoAc, 150°C



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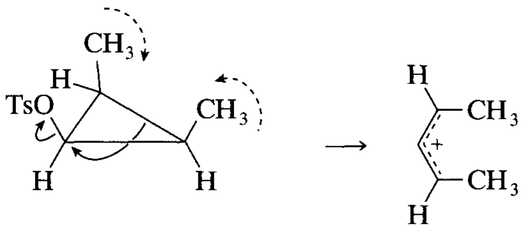
A



1

B

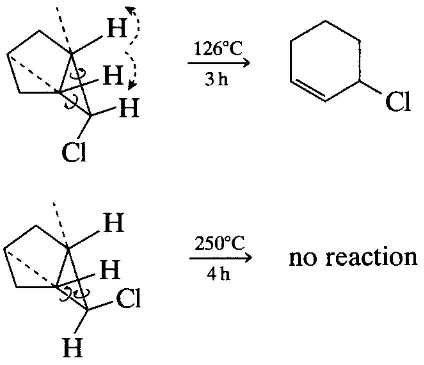
von R. Schleyer, P.; Van Dine, G. W.; Schollkopf, U.; Paust, J. *J. Am. Chem. Soc.* **1966**, *88*, 2868–2869.

The large difference in relative rates suggests that the rate-limiting step does not involve unimolecular ionization by loss of the tosyl group (an S_N1

process). If it did, we would expect that the all-*cis* isomer would react faster due to relief of steric interaction between the tosyl and methyl groups. Instead, the results can be explained by assuming that loss of the tosyl group occurs with concerted ring opening to the allyl cation and that loss of the tosyl group is assisted by backside reaction of the electrons in the breaking C—C bond of the cyclopropyl group.

As shown in the diagram, opening of a cyclopropyl cation by a disrotatory process can occur in two ways (compare the discussion of the disrotatory and conrotatory openings of the cyclobutene system). The methyl groups can rotate outward (away from one another) or inward (toward one another). Disrotatory opening in which the methyl groups rotate away from each other gives the allyl cation A, whereas if the methyl groups rotate toward each other, the result is the allyl cation B. The opening in which the methyl groups rotate outward to give allyl cation A is expected to be more favorable due to lack of steric interaction. (Note that because of the delocalized π system in the allyl cation, there is restricted rotation around the C—C bonds and A and B are not interconvertible.) When the tosyl group is *trans* to the methyl groups, the electrons move so that they can assist the loss of the tosyl group by a backside reaction reminiscent of the neighboring group effect in the S_N2 reaction. For the isomer in which the tosyl group is *cis* to the methyl groups, outward rotation of the methyl groups would result in an increase in electron density in the vicinity of the tosyl group and a consequent increase in repulsion between centers of increased electron density.

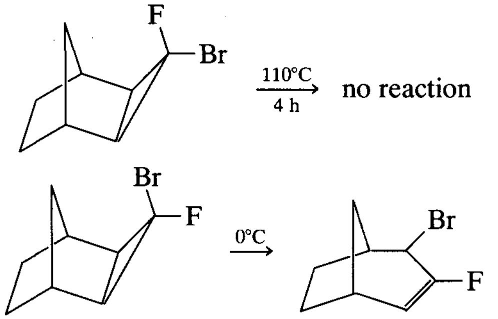
Example 6.5. ***Geometric constraint to disrotatory ring opening of a bicyclo[3.1.0]hexane system.***



Baird, M. S.; Lindsay, D. G.; Reese, C. B. *J. Chem. Soc. C* **1969**, 1173–1178.

In small, fused cyclopropyl systems, only the disrotatory mode that moves the bridgehead hydrogens outward is geometrically feasible. This means that the electrons of the breaking cyclopropyl C—C bond can assist in the loss of the chloride group only when it is *trans* to the bridgehead hydrogens.

Explain why the reactivity is so different in the following two reactions: **PROBLEM 6.5**



Jefford, C. W.; Hill, D. T. *Tetrahedron Lett.* **1969**, 1957–1960.

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3. CYCLOADDITIONS

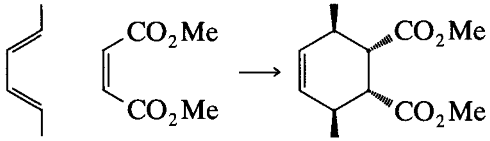
A cycloaddition is the reaction of two (occasionally more) separate π systems, in which the termini are joined to produce a ring. Cycloadditions may be intermolecular or intramolecular. One way of describing a cycloaddition is to record separately the number of electrons in each component involved in the reaction.

A. Terminology of Cycloadditions

Number of Electrons

Cycloadditions can be described on the basis of the number of electrons of each of the components. Additional symbols are used to designate the type of orbital and the type of process involved.

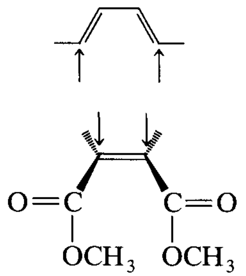
Example 6.6. ***The Diels–Alder reaction of (2E, 3E)-2,4-hexadiene and dimethyl maleate.***



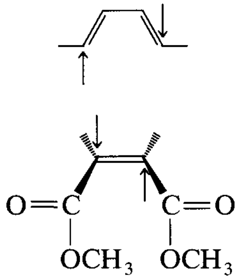
This is a six-electron process because there are four π electrons from the diene and two π electrons from the dienophile. It is also referred to as a [4 + 2] cycloaddition. Note that the carbonyl groups in the dimethyl maleate starting material are conjugated with the π bond undergoing reaction. However, because the π electrons of these carbonyl groups are not forming new bonds in the course of the reaction, they are not counted.

Stereochemistry (Suprafacial and Antarafacial Processes)

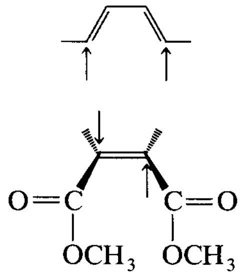
A cycloaddition reaction can be classified not only by the number of electrons in the individual components, but also by the stereochemistry of the reaction with regard to the plane of the π system of each reactant. For each component of the reaction, there are two possibilities: the reaction can take place on only one side of the plane or across opposite faces of the plane. If the reaction takes place across only one face, the process is called *suprafacial*; if across both faces, *antarafacial*. The four possibilities are shown in the following diagram:



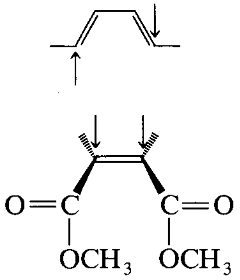
supra–supra = *syn* addition



antara–antara = *syn* addition



supra–antara = *anti* addition

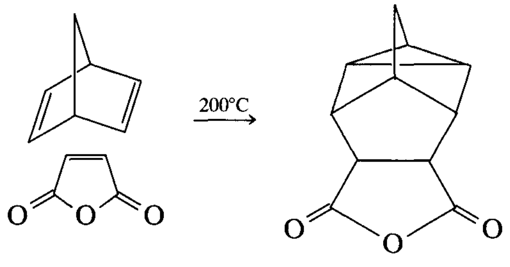


antara–supra = *anti* addition

Essentially, a *suprafacial–suprafacial* or an *antarafacial–antarafacial* cycloaddition is equivalent to a concerted *syn* addition. A *suprafacial–antarafacial* or an *antarafacial–suprafacial* process is equivalent to a concerted *anti* addition. The Diels–Alder reaction is suprafacial for both components, so that the stereochemical relationships among the substituents are maintained in the product. In Example 6.6, suprafacial addition to the dienophile component means that the two carbomethoxy groups that are *cis* in the starting material also are *cis* in the product. Suprafacial reaction at the diene component leads to a *cis* orientation of the two methyl groups in the product.

When classifying cyclizations, the subscripts "s" and "a" are used to designate suprafacial and antarafacial, respectively. Thus, a more complete designation of the Diels–Alder reaction is $[\pi_s^4 + \pi_s^2]$. This type of designation can be applied to other concerted processes, such as electrocyclic reactions, sigmatropic rearrangements, and the ene reaction; however, we will use these designations only for cycloadditions.

Example 6.7. ***A cycloaddition reaction with three π components.***



78%

Cookson, R. C.; Dance, J.; Hudec, J. *J. Chem. Soc.* **1964**, 5417–5422.

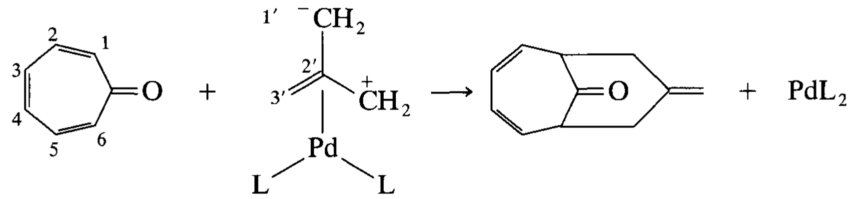
Because the two π bonds in the bicycloheptadiene are not conjugated, each is designated separately in the description of the reaction. Only the carbons, at each end of the C═C bond of maleic anhydride, are forming new bonds; thus, only the two π electrons of this bond are counted and this is a $[\pi_s^2 + \pi_s^2 + \pi_s^2]$ cycloaddition.

Number of Atoms

Some confusion has been occasioned by the introduction of another kind of terminology based on counting the number of atoms of the component systems taking part in the cycloaddition. In this system, the total number of atoms in each component is counted. This number includes both termini and all of the atoms in between. The description of a cycloaddition based on the number of atoms does not give the same designation as that based on the number of electrons.

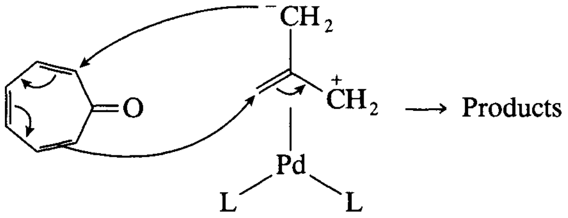
Example 6.8. ***Counting the atoms involved in a cycloaddition.***

Consider the following reaction:



Trost, B. M.; Seoane, P. R. *J. Am. Chem. Soc.* **1987**, *109*, 615–617.

The authors call this a [6 + 3] cycloaddition, because the reacting portion of tropone (the ketone) contains six atoms and the alkene component contains three atoms. The mechanism could be shown with arrows as follows:



In tropone, 6π electrons are reacting, and in the alkene, 4π electrons are reacting. Therefore, if this is a concerted reaction, it also could be called a [6 + 4] cycloaddition. If the distinction is made that [6 + 3] refers to the cycloadduct and [6 + 4] refers to the cycloaddition, the two methods of nomenclature are compatible. However, this distinction is not always made in the literature, and unless one thinks about the details of the particular reaction, the descriptions may be confusing.

B. Selection Rules for Cycloadditions

Hint 6.3 To apply the selection rules for cycloadditions, add the number of π electrons from each component undergoing reaction and then apply the rules outlined in Table 6.2.

TABLE 6.2 Stereochemical Rules for Cycloaddition Reactions

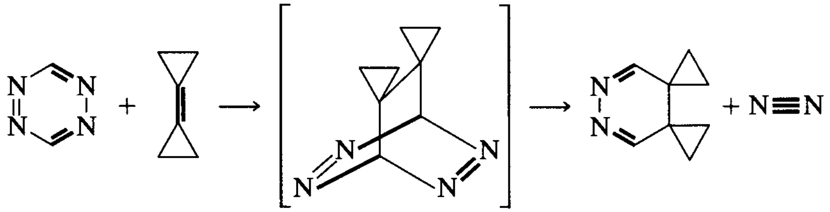
Number of electrons	*Mode of activation*	*Allowed stereochemistry*
$4n$	Thermal	Supra–antara Antara–supra
	Photochemical	Supra–supra Antara–antara
$4n + 2$	Thermal	Supra–supra Antara–antara
	Photochemical	Supra–antara Antara–supra

Many reactions encountered are of the supra–supra variety. For these systems, a good rule of thumb is that $4n$ systems are activated photochemically and $4n + 2$ systems are activated thermally.

PROBLEM 6.6

Designate the following cycloadditions according to the number of electrons contributed by each component. Is the stereochemistry shown in accordance with that predicted by the selection rules?

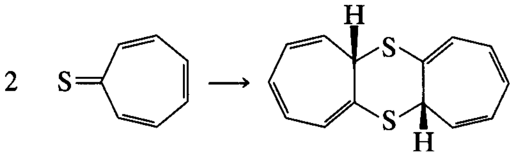
a.



de Meijere, A.; Erden, I.; Weber, W.; Kaufmann, D. *J. Org. Chem.* **1988**, *53*, 152–161.

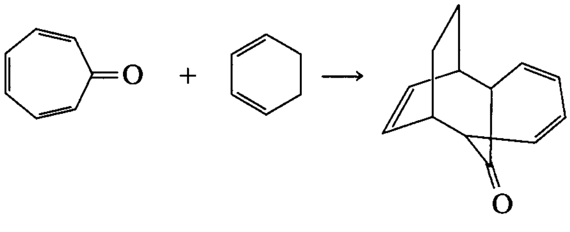
The reaction of the unstable intermediate is called a cycloreversion of retro-Diels–Alder reaction. Ordinarily it is designated by considering the reverse cycloaddition of the products of the reaction.

b.



Machiguchi, T.; Hasegawa, T.; Itoh, S.; Mizuno, H. *J. Am. Chem. Soc.* **1989**, *111*, 1920–1921.

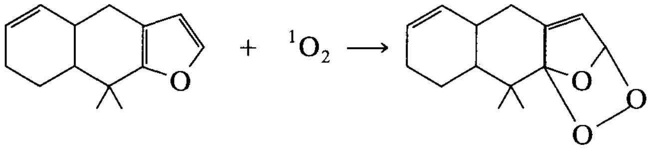
c.



Takeshita, H.; Sugiyama, S.; Hatsui, T. *J. Chem. Soc., Perkin Trans. II* **1986**, 1491–1493.

PROBLEM 6.6
continued

d.



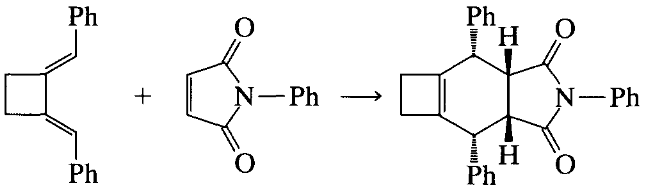
$^1O_2$ = singlet oxygen

Carte, B.; Kernan, M. R.; Barrabee, E. B.; Faulkner, D. J.; Matsumoto, G. K.; Clardy, J. *J. Org. Chem.* **1986**, *51*, 3528–3532.

PROBLEM 6.7

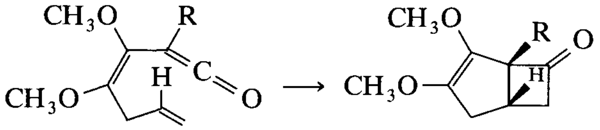
Give the complete formulation (π_s^2, etc.) for each of the following cycloadditions.

a.



Minami, T.; Harui, N.; Taniguchi, Y. *J. Org. Chem.* **1986**, *51*, 3572–3576.

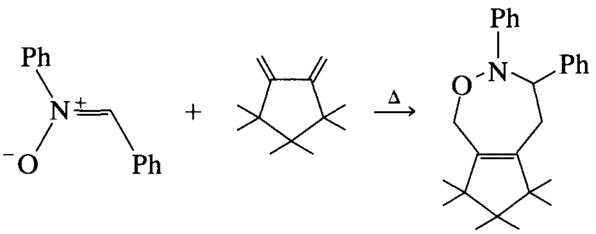
b.



Xu, S. L.; Moore, H. W. *J. Org. Chem.* **1989**, *54*, 6018–6021.

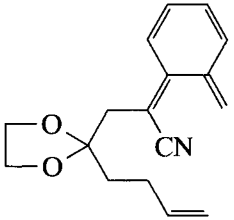
PROBLEM 6.8

If it were concerted, how would the following reaction be described by both systems of nomenclature?



Baran, J.; Mayr, H. *J. Am. Chem. Soc.* **1987**, *109*, 6519–6521.

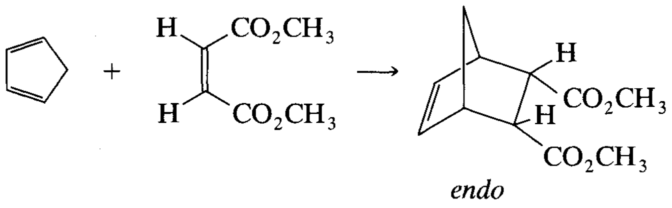
PROBLEM 6.9 **What is the product from an intramolecular [4 + 2] cycloaddition of the following molecule?**



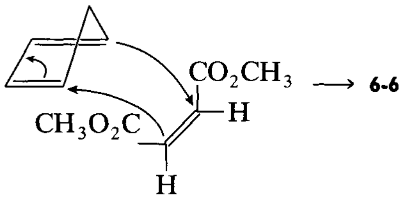
Kametani, T.; Suzuki, Y.; Honda, T. *J. Chem. Soc., Perkin Trans. I* **1986**, 1373–1377.

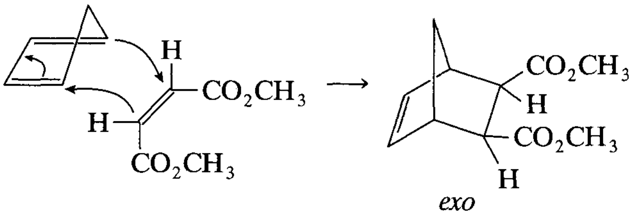
C. Secondary Interactions

In the Diels–Alder reaction of cyclopentadiene with dimethyl maleate, both *exo* and *endo* products are theoretically possible. Only the *endo* product **6-6** is found.



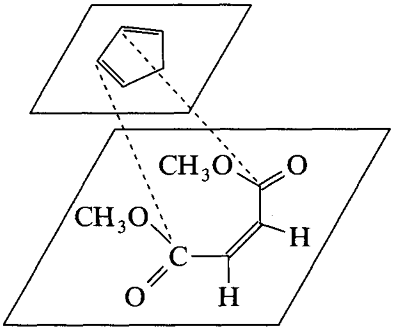
6-6





6-7

Because the carbonyl groups are part of the π system of the dienophile, there is an opportunity for secondary interactions between orbitals that are not involved in the bonding changes taking part in the cycloaddition. Molecular orbital calculations have indicated that stabilizing interactions can take place when the reactants are oriented in such a way as to produce the *endo* isomer.



These secondary attractive interactions are represented by the dashed lines between the carbonyl groups and the diene system. Visual inspection of the orientation required for *endo* addition shows that there is greater overlap of the molecular orbitals of the two components than for the orientation that leads to *exo* addition.

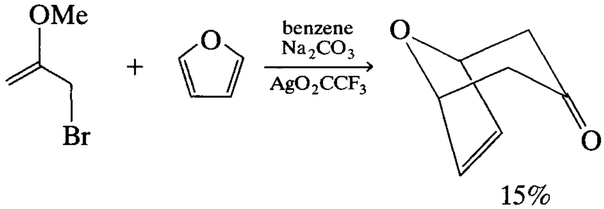
Molecular orbital interactions are only one of the factors that can influence the *exo:endo* ratio. Solvent interactions and the structure of the starting materials also are important, and these factors can result in predominantly *exo* addition products.

D. Cycloadditions of Charged Species

Allyl Cations

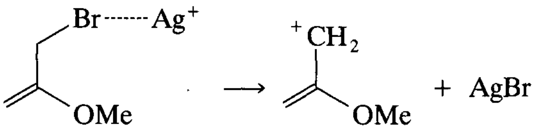
Example 6.9. ***The allyl cation as dienophile.***

A mechanism with several steps can be envisioned for the following reaction:



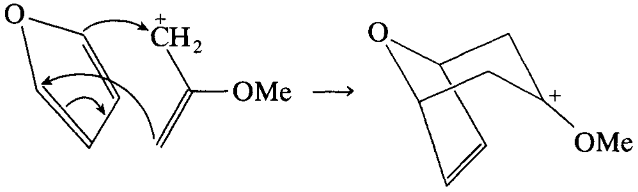
15%

The first step, ionization of the bromide to the 2-methoxyallyl cation, **6-8**, is assisted by the silver ion:



6-8

Cycloaddition occurs between cation **6-8**, which contains 2π electrons, and furan, which has 4π electrons, to give the cyclized cation, **6-9**:



6-8 **6-9**

Under the workup conditions (dilute nitric acid) **6-9** hydrolyzes to the product ketone.

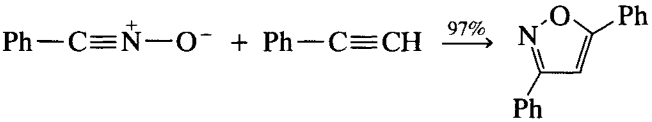
Hill, A. E.; Greenwood, G.; Hoffmann, H. M. R. *J. Am. Chem. Soc.* **1973**, *95*, 1338–1340.

1,3-Dipoles

From a synthetic standpoint, the 1,3-dipolar cycloaddition is a very important reaction. In this [4 + 2] cycloaddition, the four-electron component is dipolar in nature, and the two-electron component usually is referred to as the dipolarophile. When the thermal reaction is concerted, these reactions are suprafacial in both components, i.e., they are $[\pi_s^4 + \pi_s^2]$ cycloadditions.

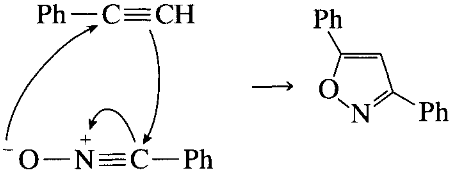
Example 6.10. ***1,3-Dipolar cycloaddition of a nitrile oxide and an alkyne.***

In the following reaction, the 4π-electron system of the nitrile oxide reacts with the 2π system of one of the acetylenic bonds.



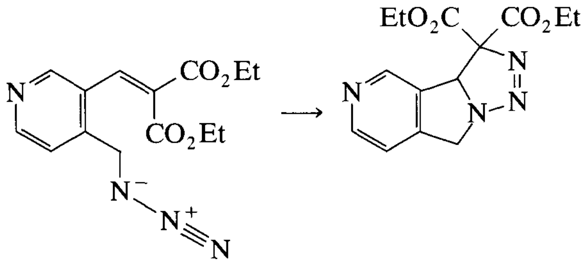
Huisgen, R. *Angew. Chem., Int. Ed. Engl.* **1963**, *2*, 565–598.

According to the newer terminology, they react to form what can be called a [3 + 2] adduct. If the mechanism is written with arrows, the usual rules apply. That is, the flow of electrons is away from negative charge and toward positive charge.



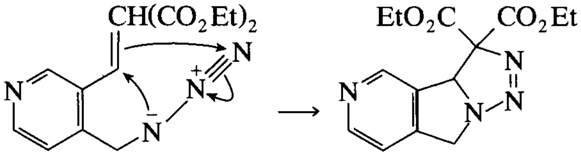
The regiochemistry of 1,3-dipolar additions can be explained on the basis of frontier orbital theory. In the examples and problems, the major products of the reactions are given. For further information, see Houk, K. N. *Acc. Chem. Res.* **1975**, 361–369.

Example 6.11. ***The intramolecular 1,3-dipolar cycloaddition of an azide.***



Tsai, C.-Y.; Sha, C.-K. *Tetrahedron Lett.* **1987**, *28*, 1419–1420.

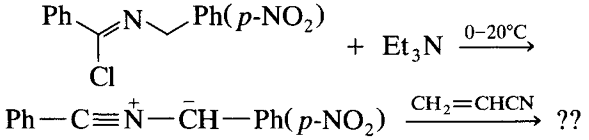
This is a concerted reaction in which four of the π electrons of the azide group undergo cycloaddition with the 2π electrons of the carbon–carbon double bond of the α-β-unsaturated ester:



These kinds of intramolecular cycloadditions are very powerful synthetic tools for the synthesis of fused ring systems.

PROBLEM 6.10

Write the possible products of the 1-3,-dipolar cycloaddition of 6-10 with acrylonitrile. Many 1,3-dipoles, like the nitrile ylide 6-10, are unstable and therefore are formed *in situ* when needed, as shown in the first step of the following reaction sequence.



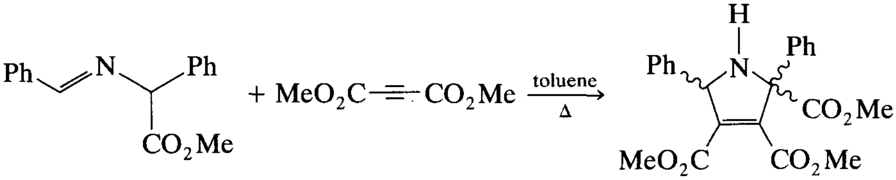
$$Ph-C\equiv\overset{+}{N}-\overset{-}{C}H-Ph(p\text{-}NO_2)\xrightarrow{CH_2=CHCN}??$$

6-10

Huisgen, R. *Angew. Chem., Int. Ed. Engl.* **1963**, *2*, 565–598.

PROBLEM 6.11

Show how the following reaction might occur.



Grigg, R.; Kemp, J.; Sheldrick, G.; Trotter, J. *J. Chem. Soc., Chem. Commun.* **1978**, 109–111.

4. SIGMATROPIC REARRANGEMENTS

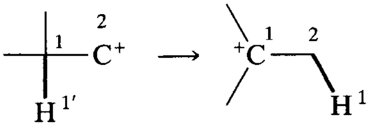
A. Terminology

In a sigmatropic reaction, movement of a σ bond takes place, producing rearrangement (tropic is from the Greek word "tropos," to turn). Common types of sigmatropic reactions are the familiar 1,2-hydride or alkyl shifts in carbocations and the Cope rearrangement.

Sigmatropic reactions can be designated by the same scheme we have used for π electron reactions, i.e., $[\pi_s^4 + \sigma_s^2]$, etc. However, sigmatropic reactions are more often designated in a different way.

Hint 6.4 To determine the order of a sigmatropic reaction, first label both atoms of the original (breaking) σ bond as 1. Then count the atoms along the chains on both sides until you reach the atoms that form the new σ bond. The numbers assigned to these atoms are given in brackets, separated by a comma, e.g., [1,5] or [3,3]. This nomenclature is illustrated in Examples 6.12 through 6.14.

Example 6.12. ***A [1,2] sigmatropic shift in a carbocation.***

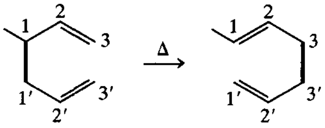


The σ bond that is broken in the starting material and the σ bond formed in the product are highlighted. Hydrogen (1′) has moved from carbon 1 to carbon 2, so that the reaction is designated as a [1,2] sigmatropic shift. The 1 of this designation does not refer to the number on carbon, but to the number on hydrogen. This indicates that the same atom (hydrogen) is at one end of the σ bond in both starting material and product. The 2 of the designation, [1,2], is the number of the carbon where the new σ bond is formed, relative to the number 1 for the carbon where the old σ bond was broken.

This reaction can also be designated as $[\pi_s^0 + \sigma_s^2]$. This is more appropriate than labeling the reaction as $[\pi_s^2 + \sigma_s^0]$, because this is considered to be a hydride shift, not a proton shift.

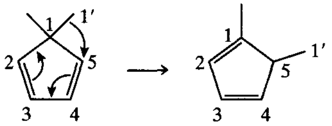
Example 6.13. *A [3,3] sigmatropic shift.*

Consider the classical Cope rearrangement:



The atoms at the ends of the σ bond being broken are numbered 1 and 1′. Atoms are then numbered along each chain until the atoms at the ends of the new σ bond are reached. The atoms of the new σ bond are numbered 3 and 3′. Formally, the σ bond, originally at the 1,1′ position, has moved to the 3,3′ position. Thus, this is called a [3,3] sigmatropic shift.

Example 6.14. *A [1,5] sigmatropic shift.*

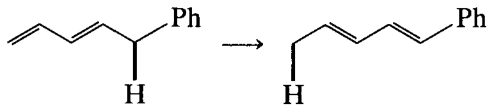


All of the carbons in the ring must be counted as part of the process. That is, this reaction is *not* a simple [1,2] shift, because the π electrons in the ring also must rearrange. Thus, this is a [1,5] shift.

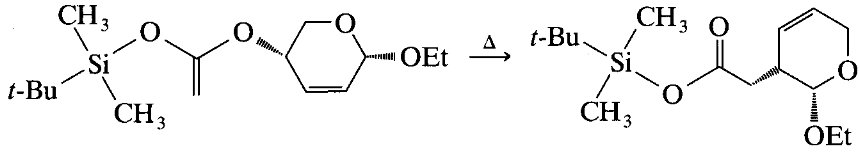
Designate the type of sigmatropic shift that occurs in each of the following reactions (e.g., [1,3]). Also give the appropriate reaction designation. **PROBLEM 6.12**

PROBLEM 6.12
continued

a.

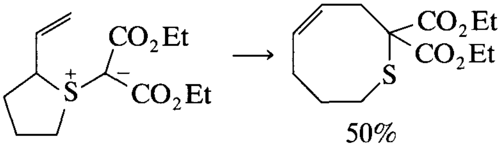


b.



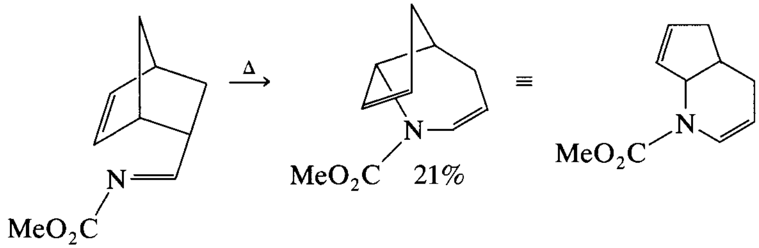
Curran, D. P.; Jacobs, P. B.; Elliott, R. L.; Kim, B. H. *J. Am. Chem. Soc.* **1987**, *109*, 5280–5282.

c.



Vedejs, E. *Acc. Chem. Res.* **1984**, *17*, 358–364.

d.



Wu, P.-L.; Chu, M.; Fowler, F. W. *J. Org. Chem.* **1988**, *53*, 963–972.

B. Selection Rules for Sigmatropic Rearrangements

For sigmatropic reactions, as for electrocyclic reactions and cycloadditions, the course of reaction can be predicted by counting the number of electrons involved and applying the selection rules. A comprehensive rationalization of all the stereochemical aspects of these reactions requires application of the frontier orbital or orbital symmetry approaches, and, at this point, we will content ourselves with pointing out the salient features of the more common reactions of this class.

TABLE 6.3 Selection Rules for Sigmatropic Hydrogen Shifts

Order	*Number of electrons*	*Mode of activation*	*Allowed stereochemistry*
[1,3]	4*n*	Thermal	Antarafacial
		Photochemical	Suprafacial
[1,5]	4*n* + 2	Thermal	Suprafacial
		Photochemical	Antarafacial
[1,7]	4*n*	Thermal	Antarafacial
		Photochemical	Suprafacial

Hint 6.5

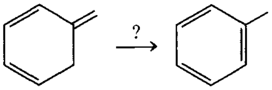
For a sigmatropic reaction, the number of electrons involved is the number of π electrons plus the pair of electrons in the migrating σ bond.

Hydrogen Shifts

Thermal [1,3] hydrogen shifts are unknown. The migrating hydrogen must maintain overlap with both ends of the π system, but the geometry required by antarafacial migration makes this impossible. A few photochemical [1,3] hydrogen shifts are known. Because the hydrogen moves suprafacially with photochemical activation, the reaction is geometrically feasible, as well as being symmetry-allowed.

PROBLEM 6.13

The following compound has been prepared and is stable at dry ice temperatures (−78°C), even though its isomer, toluene, an aromatic compound, is much more stable. Why is it possible to isolate the nonaromatic triene?



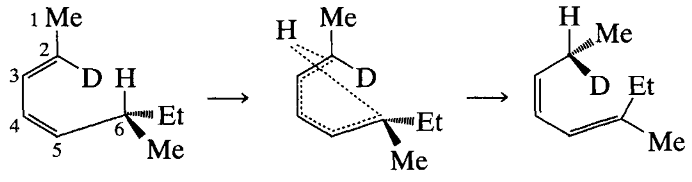
Bailey, W. J.; Baylouny, R. A. *J. Org. Chem.* **1962**, *27*, 3476.

Example 6.15. *The stereochemical consequences of a concerted, thermally allowed [1,5] sigmatropic shift.*

An elegant demonstration of the stereochemistry of a thermally allowed [1,5] sigmatropic shift was reported by Roth and coworkers in 1970. They studied the stereochemistry of the reaction of the optically active starting material,

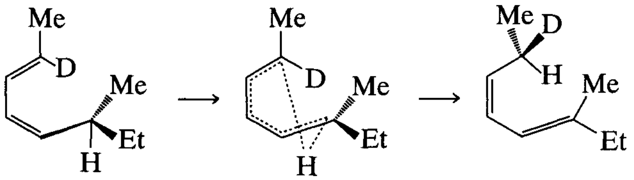
6-11. There are four possible products: two arise from suprafacial reaction and two more from antarafacial reaction.

Suprafacial rearrangement of hydrogen across the *top* face of the π system gives **6-12**.



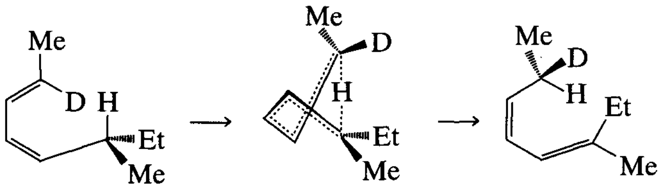
6-11 **6-12**

Rotation about the C-5—C-6 bond axis gives a new conformation of **6-11**. The suprafacial movement of hydrogen across the *bottom* face of the π system in this conformation produces **6-13**, a geometric isomer of **6-12**.

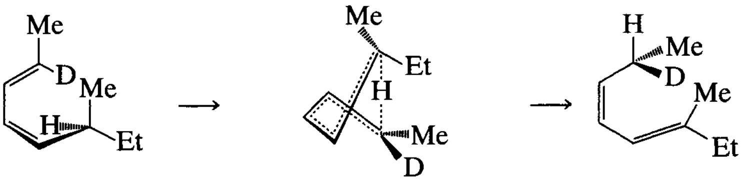


6-11 **6-13**

Antarafacial movement of hydrogen also gives two possible products, **6-14** and **6-15**. In the reaction to give **6-14**, hydrogen moves from the top face to the bottom face; in the reaction to give **6-15**, hydrogen moves from the bottom face to the top face.



6-11 **6-14**

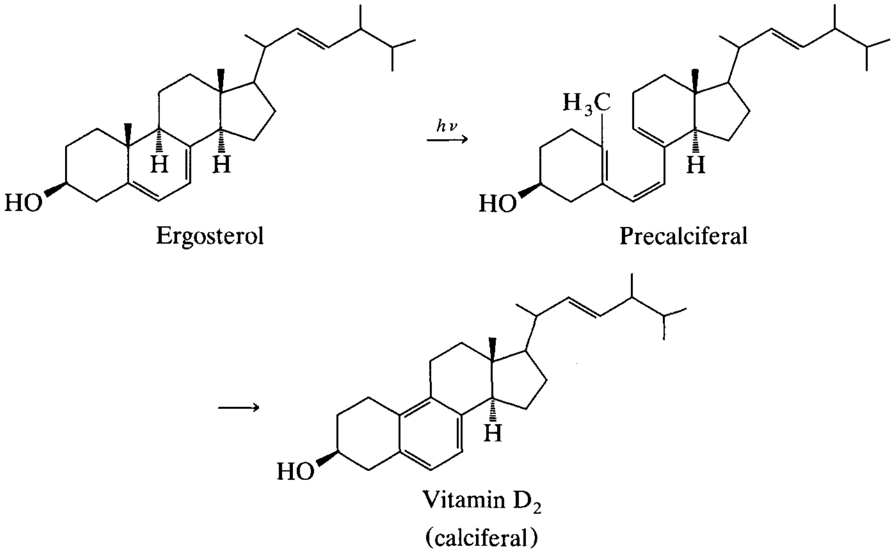


6-11 **6-15**

In agreement with the theoretical prediction of suprafacial reaction, compounds **6-12** and **6-13** were produced rather than **6-14** and **6-15**. Because of the favorable geometry for suprafacial migration, there are many examples of thermal [1,5] sigmatropic shifts, which occur with ease.

These elegant experiments are reported by Roth, W. R.; Konig, J.; Stein, K. *Chem. Ber.* **1970**, *103*, 426–439.

The industrial synthesis of vitamin D_2 involves two pericyclic processes. Identify these processes in the following transformations and comment on the stereochemistry observed. **PROBLEM 6.14**



Schlatmann, J. L. M. A.; Pot J.; and Havinga, E. *Recl. Trav. Chim. Pays-Bas* **1964**, *83*, 1173.

Alkyl Shifts

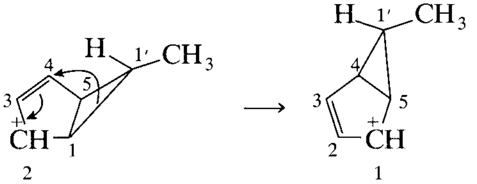
When an alkyl group migrates, there is an additional stereochemical aspect to consider, namely, the carbon atom can migrate with inversion or retention of configuration. Commonly encountered processes include suprafacial [1,3] shifts with inversion and suprafacial [1,5] shifts with retention. (Note that this contrasts with the case for hydrogen migration, where the [1,3] shift is antarafacial and the [1,5] shift is suprafacial.) Inversion at carbon is an antarafacial process because the bond formed is on the opposite side of the carbon atom to the bond broken; retention at carbon is a suprafacial process.

TABLE 6.4 Selection Rules for Sigmatropic Alkyl Shifts

Number of electrons	*Mode of activation*	*Allowed stereochemistry*
$4n$	Thermal	Suprafacial with inversion
	Photochemical	Antarafacial with retention
$4n + 2$	Thermal	Suprafacial with retention
	Photochemical	Antarafacial with inversion

Example 6.16. ***Sigmatropic shifts in the* exo*-6-methylbicyclo[3.1.0]hexenyl cation.***

This is an interesting example of the stereochemical consequences of orbital symmetry. In this cation, the *exo*-6-methyl group remains *exo* as the migration of carbon-6 proceeds around the ring.



(Note that the numbers shown in the equation are not those used to name the compound. Thus, the 1′ carbon is numbered 6 for nomenclature purposes, and the methyl on this carbon is referred to as the *exo*-6-methyl.)

Inspection of the structures involved might suggest that the electrons of the C-1—C-1′ bond can "slide over" to form the C-4—C-1′ bond, as represented by the arrows in the structure. If this is the reaction pathway, the configuration at C-1′ is maintained because both bond breakage and bond formation occur at the same location relative to C-1′, and we would expect to see the methyl group change from an *exo* to an *endo* orientation because of the rotation required about the C-5—C-1′ bond. Consideration of the selection rules leads to a different prediction.

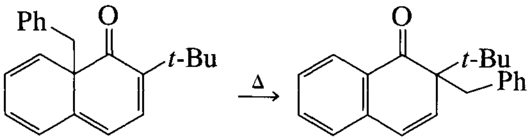
By applying Hint 6.4, we can classify the reaction as a [1,4] sigmatropic shift. Counting the electrons in the bonds undergoing rearrangement shows that there are four electrons involved; consequently, a thermal process should proceed suprafacially with inversion at the migrating carbon. This means that in the bicyclo[3.1.0]hexenyl cation, bond breaking and bond formation occur on opposite sides of C-1′, so that the methyl group remains in the *exo* position. Because these transformations frequently are difficult to visualize, molecular models are very useful for studying these kinds of reactions.

For the actual structures studied, see Hart, H.; Rodgers, T. R.; Griffiths, J. *J. Am. Chem. Soc.* **1969**, *91*, 754–756.

PROBLEM 6.15

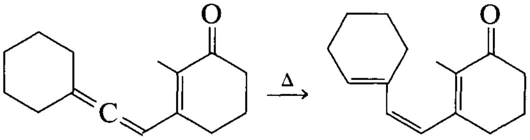
Show how the following concerted processes can be explained on the basis of one or more sigmatropic shifts. What are the designations for the shift(s) involved?

a.



Miller, B.; Baghdadchi, J. *J. Org. Chem.* **1987**, *52*, 3390–3394.

b.



Barrack, S. A.; Okamura, W. H. *J. Org. Chem.* **1986**, *51*, 3201–3206.

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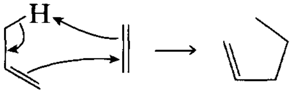
5. THE ENE REACTION

The ene reaction appears to combine the characteristics of cycloaddition and sigmatropic reactions.

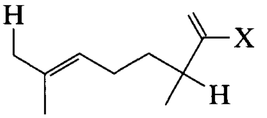


This looks similar to the Diels–Alder reaction, in which a C—H bond replaces the double bond of the diene component. In some cases, the ene reaction actually competes with the Diels–Alder reaction. Because of the similarities, the allyl component often is called the enophile, and the other component is called the ene.

The ene reaction also can take place intramolecularly and, thus, lead to new rings.

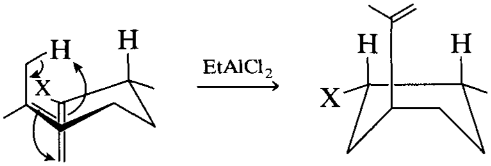
Example 6.17. ***An intramolecular ene reaction.***

The unconjugated diene, **6-16**, reacts to form a cyclic molecule.



$X = CO_2Me$

6-16



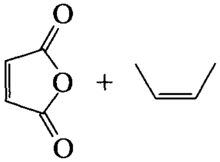
6-16

82%

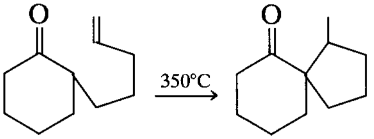
Because the proton is transferred to the top of the double bond, the carbomethoxy group, X, is forced down. Molecular models are extremely useful for visualizing the conformation of **6-16** needed for cyclization to take place. *Cautionary note:* there is no evidence that this is a concerted reaction.

Snider, B. B.; Phillips, G. B. *J. Org. Chem.* **1984**, *49*, 183–185.

PROBLEM 6.16 Draw the product for the ene reaction of the following components:



Propose a mechanism for the following cyclization. **PROBLEM 6.17**

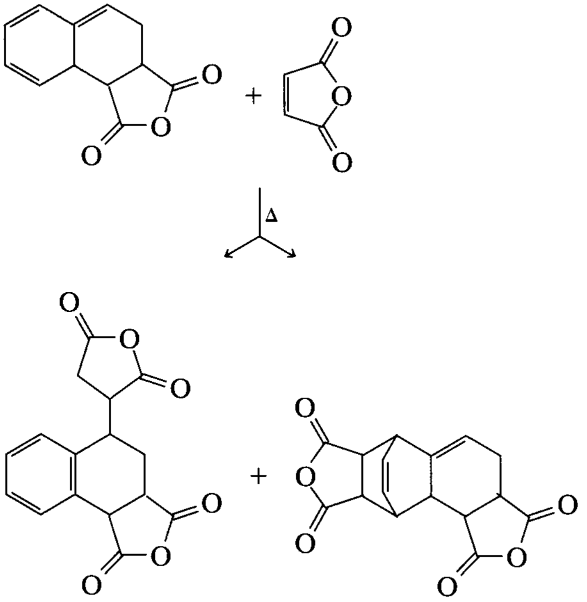


100%

Conia, J.; Robson, M. J. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 473.

Write appropriate mechanisms for each of the following reactions. **PROBLEM 6.18**

a.

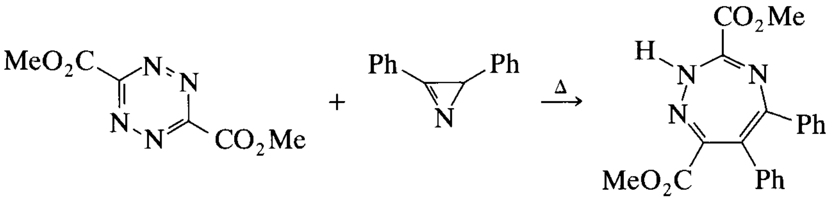


89% of product 11% of product

Alder, K.; Schmitz-Johnson, R. *Ann.* **1955**, *595*, 1–37; Hoffmann, H. M. R. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 556–577.

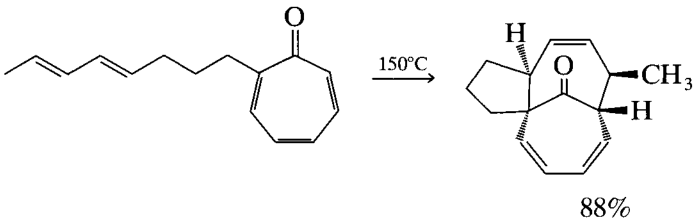
PROBLEM 6.18
continued

b.



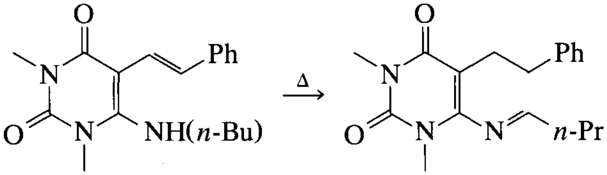
Johnson, G. C.; Levin, R. H. *Tetrahedron Lett.* **1974**, 2303–2307.

c.



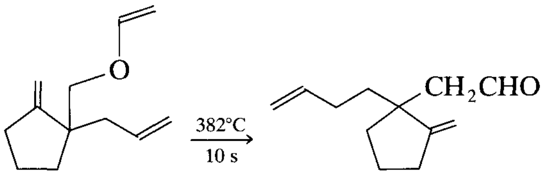
Funk, R. L.; Bolton, G. L. *J. Am. Chem. Soc.* **1986**, *108*, 4655–4657.

d.



Matyus, P.; Zolyomi, G.; Eckhardt, G.; Wamhoff, H. *Chem. Ber.* **1986**, *119*, 943–949.

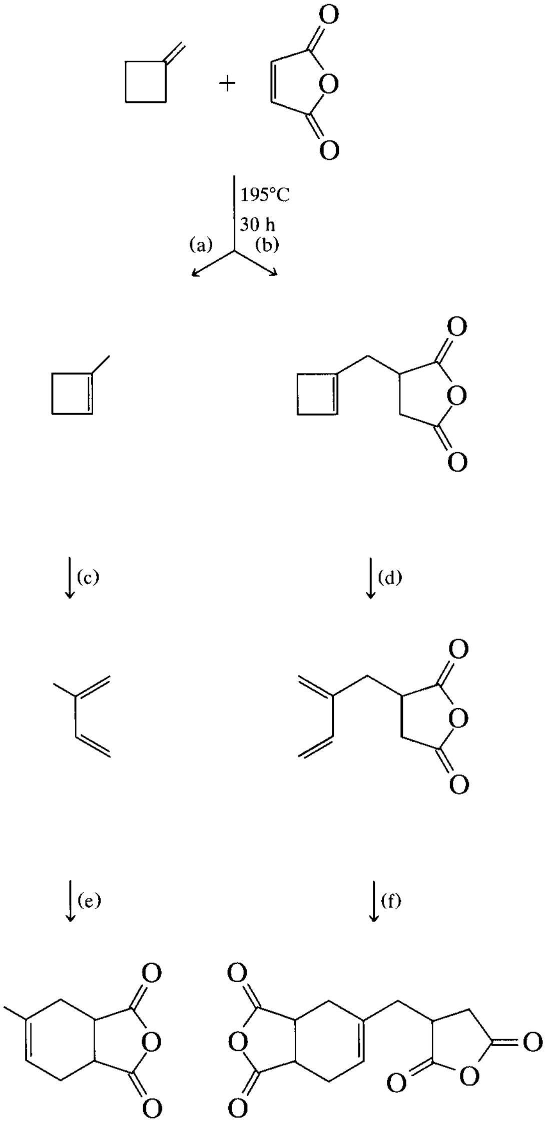
e.



Ziegler, F. E.; Piwinski, J. J. *J. Am. Chem. Soc.* **1982**, *104*, 7181–7190.

PROBLEM 6.18
continued

f.

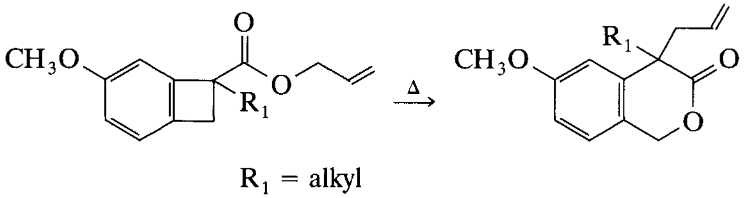


Alder, K.; Dortmann, H. A. *Chem. Ber.* **1952**, *85*, 556–565.

PROBLEM 6.19

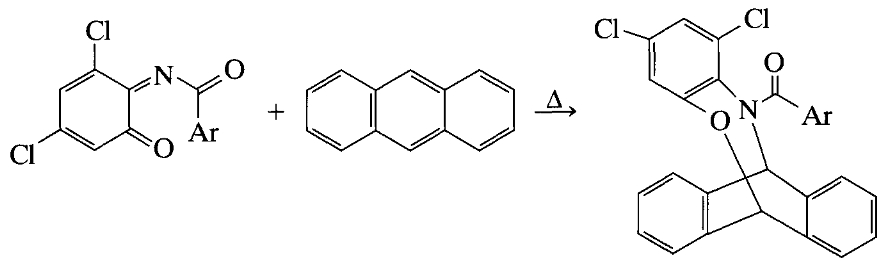
The following thermal transformation involves three pericyclic changes. The first two are electrocyclic and the third is a sigmatropic rearrangement. Give structures for the two intermediates in the reaction.

PROBLEM 6.19
continued



Shishido, K.; Shitara, E.; Fukumoto, K.; Kametani, T. *J. Am. Chem. Soc.* **1985**, *107*, 5810–5812.

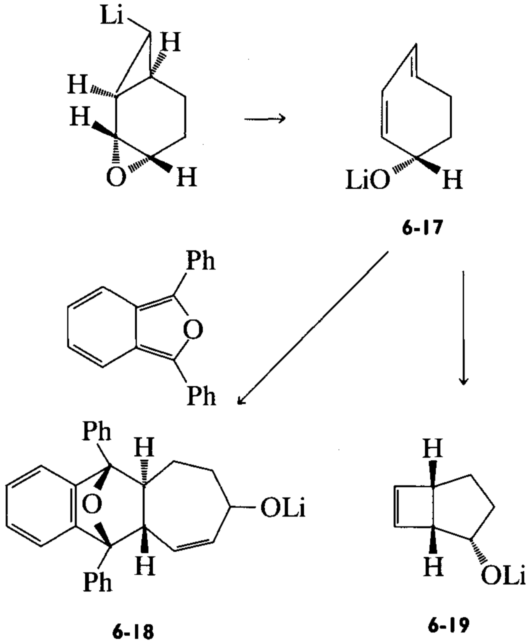
PROBLEM 6.20 **The following equation represents a thermal [4 + 4] cycloaddition, which occurs readily. Discuss orbital symmetry considerations in detail and propose a mechanism for the reaction.**



Heine, H. W.; Suriano, J. A.; Winkel, C.; Burik, A.; Taylor, C. M.; Williams, E. A. *J. Org. Chem.* **1989**, *54*, 5926–5930.

PROBLEM 6.21 **Transformation of starting material to 6-17 involves a concerted electrocyclic transformation, followed by anion-promoted ring opening of the epoxide. The other transformations are one-step concerted processes. Explain the stereochemical preferences of each reaction. Why is the electrocyclic transformation of 6-17 to 6-19 favored when such reactions usually occur more readily in the opposite direction?**

PROBLEM 6.21
continued



Coates, R. M.; Last, L. A. *J. Am. Chem. Soc.* **1983**, *105*, 7322–7326.

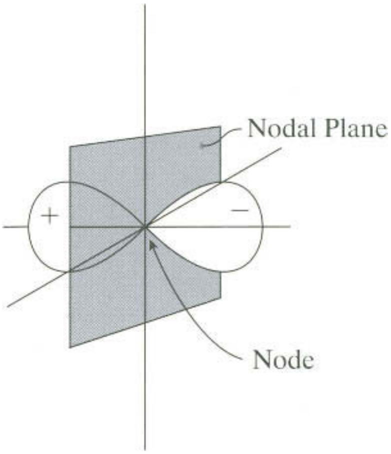
6. A MOLECULAR ORBITAL VIEW OF PERICYCLIC PROCESSES

Although electron counting and application of the selection rules provide a practical method of analyzing and predicting pericyclic reactions, a greater understanding of these reactions can be gained by analyzing the molecular orbitals involved. A quantitative mathematical approach is of interest for a detailed analysis of specific reactions, but qualitative analysis can be applied much more rapidly and with very good effect to a much larger number of systems. The theory and methods of the molecular orbital approach to pericyclic reactions are beyond the scope of this book. We simply provide some introductory material on how to derive molecular orbitals for the π systems involved in pericyclic reactions, along with a few illustrative examples of how molecular orbital theory looks at selected pericyclic reactions.

A. Orbitals

An orbital, whether atomic or molecular, represents the region of space where a particular electron is most likely to be found. Orbitals are derived by solving wave equations, which are based on the experimental finding that electrons, like photons, can behave like waves as well as like particles. The wave equations that can be written for the electrons associated with individual atoms are analogous to the equations that can be written to describe a standing wave in a vibrating string. This is a useful analogy because a wavefunction has amplitude and nodes, just like the standing waves in a vibrating string. For a given electron, the probability of finding an electron at a particular location can be obtained by squaring the amplitude given by the wavefunction. Plotting of these probabilities gives a visual representation of the orbital shape and electron density.

Hint 6.6 A node, where the amplitude and electron density are zero, separates an orbital into lobes that have different algebraic signs. An atomic *s* orbital has no nodes, whereas in an atomic *p* orbital a nodal plane divides the orbital into two lobes of differing sign.



Atomic *p* orbital

In the diagram used in this chapter, the sign of the amplitude is represented by + and − signs within the lobes of the orbital. (An alternative representation uses shaded or unshaded lobes.)

B. Molecular Orbitals

Molecular orbitals (MOs) are derived mathematically by a linear combination of the wavefunctions for the atomic orbitals (AOs) of the individual atoms in a molecule. Usually, only the atomic orbitals of the valence electrons are considered, because these are the electrons involved in bonding. We can visualize the formation of MOs as proceeding from overlap of the AOs of the valence electrons.

Just as we can consider the *formation of molecules* from atoms in terms of the *interaction of atomic orbitals* to form molecular orbitals, we can consider *reactions of molecules*, both intramolecular and intermolecular, in terms of the *interaction of the molecular orbitals*. In the case of pericyclic reactions, a very useful simplification can be made on the basis of Huckel molecular orbital theory. We assume that, because the *p* orbitals that overlap to form π bonds are orthogonal (lie at right angles) to the σ bonds, the π bonding system can be considered independently of the single (σ) bonds in the reacting molecules and that the π bonding system is the most important factor in determining the chemical reactivity of conjugated polyenes and aromatic compounds.

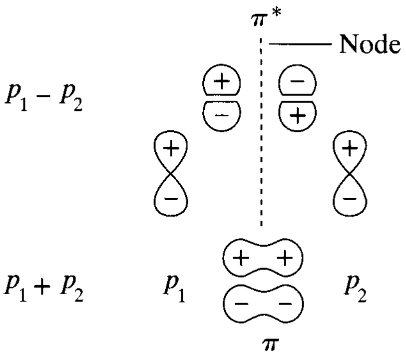
Hint 6.7

Molecular orbitals can be classifed with regard to three elements:

1. The number of nodes
2. Symmetry with respect to a mirror plane (σ)
3. Symmetry with respect to rotation about a two-fold axis (C_2)

For each molecular orbital in a molecule, the classification according to these three characteristics is unique. In other words, for any molecule these three descriptors cannot be identical for two different molecular orbitals.

In molecular orbitals, as in atomic orbitals, *nodes* are regions of zero electron density that divide an orbital into lobes with amplitudes of opposite sign. When a node coincides with a nuclear position, there are no lobes depicted on that atom. In the following diagram, we see that the bonding π molecular orbital for ethylene has no nodes perpendicular to the bond axis, whereas the antibonding π^* orbital has one node perpendicular to the bond axis.

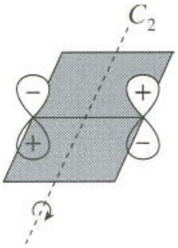


Electron distribution of atomic *p* orbitals and molecular orbitals (π and π^*).

The orbital representation is an approximation of the electron distribution.

The symmetry of a π system can be examined with respect to a *mirror plane* bisecting the π system and perpendicular to the σ bond molecular framework. (A mirror plane similarly bisects a fork or a spoon.) An orbital is symmetric (S) with respect to a mirror plane (usually called a σ plane) if it has the same sign on both sides, and antisymmetric (A) if the two sides have opposite sign. For example, in ethylene the bonding π orbital is symmetric with respect to the mirror plane, whereas the antibonding orbital is antisymmetric, as shown in Table 6.5. Note that antisymmetric does *not* mean the same as asymmetric.

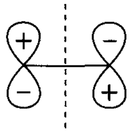
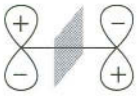
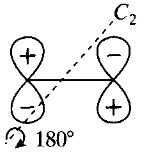
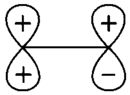
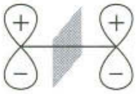
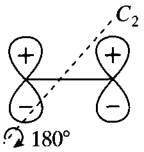
The symmetry of a π system also can be classified with respect to *rotation about a C_2 axis bisecting the π system and lying in the plane defined by its σ bond framework*. A C_2 axis is defined operationally: rotation of 180° about a C_2 axis gives an arrangement indistinguishable from the original. (A twin-bladed fan or propeller is an everyday object with a C_2 axis. A flathead screwdriver has both a mirror plane and a C_2 axis.) The following diagram shows the C_2 axis for the antibonding π^* orbital in ethylene. When the orbitals are rotated 180° with respect to this axis, the + and − orbitals coincide with the + and − orbitals of the original arrangement.



C. Generating and Analyzing π Molecular Orbitals

In analyzing the π molecular orbitals of reacting molecules, we need to determine the number of orbitals, their relative energy, and the number and placement of nodes. Once we have determined the number and relative energy of the orbitals, we can determine the electron configurations of the reactants and analyze the amplitudes of the orbitals that overlap in the course of the reaction.

TABLE 6.5 Symmetry Characteristics of Ethylene π Molecular Orbitals

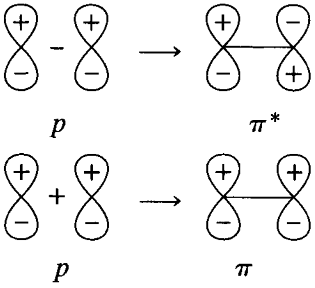
	Molecular orbital	*Reflection through mirror plane (σ)*	*Rotation about the C_2 axis*
π*	 Nodes = 1	 Antisymmetric (A)	 Symmetric (S)
π	 Nodes = 0	 Symmetric (S)	 Antisymmetric (A)

The number of molecular orbitals is equal to the number of atomic orbitals that was used to construct them.

Hint 6.8

Example 6.18. ***The π molecular orbitals of ethylene.***

For ethylene ($H_2C{=}CH_2$), the simplest π system, there are two ways that we can combine the two *p* atomic orbitals from the two carbon atoms so that we get two π molecular orbitals.

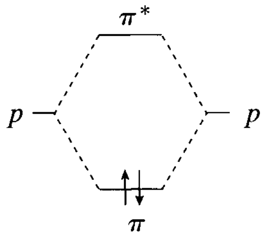


Basis sets and molecular orbitals for ethylene.

If the wavefunctions for the two p orbitals are added, we form a bonding orbital (π); if the wavefunctions are subtracted, we form an antibonding orbital (π^*). Molecular π orbitals are commonly represented by the atomic orbitals that combine to form them. In the accompanying diagram, the orbitals on the left are the atomic orbitals. These are used to form the molecular orbitals of ethylene, which appear on the right. The atomic orbitals that are combined to form the molecular orbitals are called the *basis set*.

Hint 6.9 **When atomic orbitals are combined to give molecular orbitals, the molecular orbitals can be bonding, antibonding, or nonbonding. The number of bonding and antibonding orbitals is equal. If the number of atomic orbitals used is odd, there is a nonbonding orbital in addition to the bonding and antibonding orbitals.**

Electrons in the bonding (π) orbital are lower in energy than electrons in the isolated p orbitals, and electrons in the antibonding (π^*) orbital are higher in energy than electrons in the isolated p orbitals, as illustrated here for ethylene.



Energy levels of π molecular orbitals for ethylene.

The energy of a nonbonding orbital is comparable to that of the p orbitals of the isolated atoms.

Hint 6.10 **For linear, conjugated polyenes, each molecular orbital has a unique energy.**

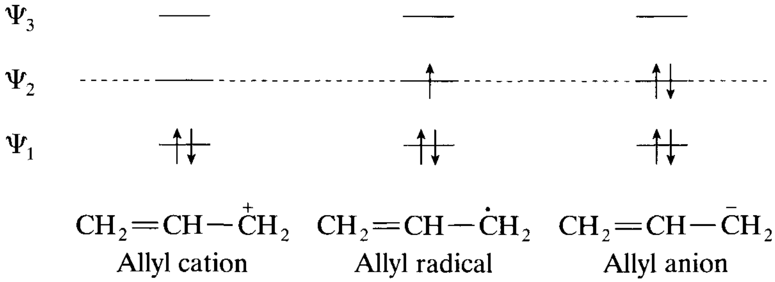
The conjugated polyene systems taking part in pericyclic reactions are linear, so all the π molecular orbitals of the starting materials have a different energy. The distribution of energy levels is important because it affects the electronic configuration of the starting materials (see Example 6.19) and consequently the course of the reaction.

In symmetrical *cyclic conjugated* systems, such as benzene, there are sets of molecular orbitals with the same energy (degenerate orbitals). (The pattern of energy levels for these aromatic systems can be determined by Frost diagrams, which we will not consider; see Carey, F. A.; Sundberg, R. J. *Advanced Organic Chemistry, Part A: Structure and Mechanism*, 3rd ed; Plenum Press: New York, 1990; pp. 44–46.) The symbol Ψ is commonly used to designate the various molecular orbitals, which are distinguished by subscripts (i.e., in order of increasing energy, Ψ_1, Ψ_2, $\Psi_3, \ldots$).

Hint 6.11

We determine the electron configuration for molecular π electrons in the same way that we do for atomic electron configurations: we count the total number of electrons and then use these to fill each orbital with a maximum of two electrons, starting with the lowest energy orbital and filling the orbitals in order of increasing energy.

Example 6.19. ***Energy levels for the allyl molecular orbitals and electron configurations of the allyl cation, radical, and anion.***



The molecular orbitals of the allyl system are formed by the overlap of three atomic *p* orbitals. Because there is an odd number of atomic orbitals, one of the molecular orbitals is a nonbonding orbital, whose energy is comparable to that of the isolated *p* orbitals from which it was derived. Note that if there were degenerate molecular orbitals in the allyl system, the electronic configurations of various allyl species would be different. For example, if Ψ_2 and Ψ_3 for the allyl system had identical energy levels, the allyl anion would have two unpaired electrons.

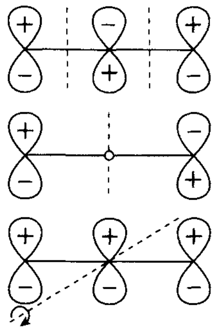
Hint 6.12

The molecular orbital of lowest energy has no nodes, the next has one node, the next two nodes, and so on. The nodes are arranged symmetrically with respect to the center of a linear π system.

Nodes in the π molecular orbitals bisect the bonds forming the σ framework; for π systems derived from an odd number of atomic orbitals, nodes may also coincide with nuclei (see Example 6.20).

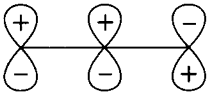
Hint 6.13 If the molecular orbitals are examined in order of increasing energy, the orbitals alternate in symmetry with regard to the mirror plane and C_2 axis of symmetry. The first orbital is symmetric (S) with respect to a mirror plane bisecting the linear system, the second orbital is antisymmetric (A) with respect to the same plane, and so on. Similarly, the first orbital is antisymmetric with respect to the C_2 axis, the second is symmetric with respect to C_2, and so on.

Example 6.20. ***Molecular orbitals of the allyl system.***

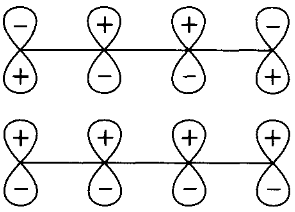


	Nodes	Symmetry: Mirror (σ)	Symmetry: C_2
Ψ_3	2	S	A
Ψ_2	1	A	S
Ψ_1	0	S	A

PROBLEM 6.22 **Why would the following molecular orbital diagram for the allyl system be incorrect?**



Explain why the following would not be the two lowest energy MOs for 1,3-butadiene. **PROBLEM 6.23**



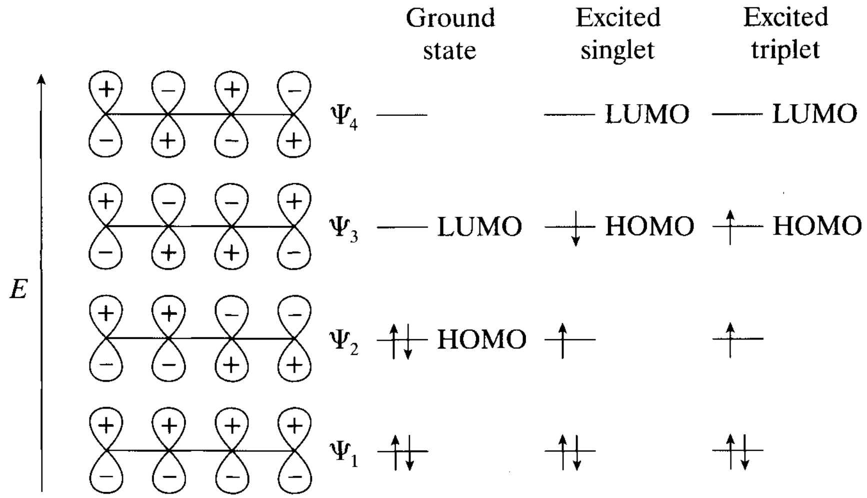
Write all the MOs for the four- and five-carbon π systems. Indicate the number of nodes and designate the symmetry of each orbital with respect to the mirror plane (σ) and the C_2 axis of rotation. **PROBLEM 6.24**

D. HOMOs and LUMOs

In analyzing pericyclic reactions, two molecular orbitals are of particular interest: the π molecular orbital of highest energy that contains one or two electrons (the highest occupied molecular orbital, HOMO) and the molecular orbital of lowest energy that contains no electrons (the lowest unoccupied molecular orbital, LUMO). For electrocyclic reactions, where there is only one π system, the important orbital is the HOMO. When more than one π system is involved, as in cycloaddition, reactions are considered to occur through a transition state in which the HOMO of one component overlaps the LUMO of the other.

In photochemically activated reactions, the HOMO and LUMO are not the same as those for thermal reactions because absorption of light promotes an electron from the HOMO to the LUMO of the ground state. Thus, the LUMO of the ground state becomes the HOMO of the photochemically excited state.

Example 6.21. ***HOMOs and LUMOs for the butadiene system.***



PROBLEM 6.25 **By using the orbitals drawn for Problem 6.24, indicate the electronic configuration for the pentadienyl cation, radical, and anion. Label the HOMO and LUMO for each case.**

Hint 6.14 For bond formation to occur, the overlapping (i.e., interacting) molecular orbitals must have amplitudes of like sign.

Bond formation during reactions is entirely analogous to the process whereby we form molecular orbitals from atomic orbitals in individual molecules. Interaction between orbitals of like sign results in constructive interference (i.e., bonding), whereas interaction between orbitals of opposing sign results in destructive interference.

E. Correlation Diagrams

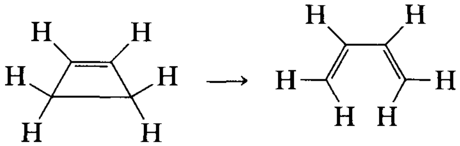
In a pericyclic reaction, the pathway predicted by the selection rules is the one that allows maximum orbital overlap along the reaction pathway, including the transition state. Maximum orbital overlap corresponds to the path of minimum energy and is achieved if the orbitals involved are similar in energy and if the symmetry of the orbitals is maintained throughout the reaction path.

When pericyclic reactions are analyzed in terms of correlation diagrams, all of the π and σ molecular orbitals taking part in the reaction are analyzed in terms of their symmetry properties with respect to reflection in a mirror plane and rotation about a C_2 axis. The symmetry elements of importance are those that are found in both reactants and products *and* are preserved during the course of the reaction. If the symmetry properties of all of the orbitals remain unchanged (are conserved) throughout the reaction, then maximum orbital interaction is maintained throughout the course of the reaction and the reaction is *symmetry-allowed.* If the symmetry properties change, then the reaction is *symmetry-forbidden.*

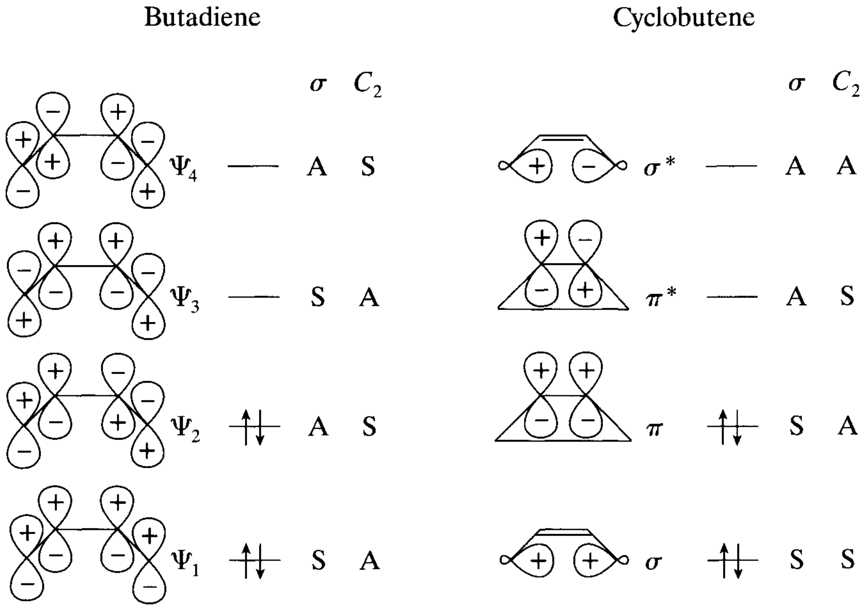
Example 6.22. ***Orbital correlation diagrams for the interconversion of butadiene and cyclobutene.***

Classifying the Relevant Orbitals

As in the electron-counting approach, we consider only the electrons and bonds that change in the reaction.

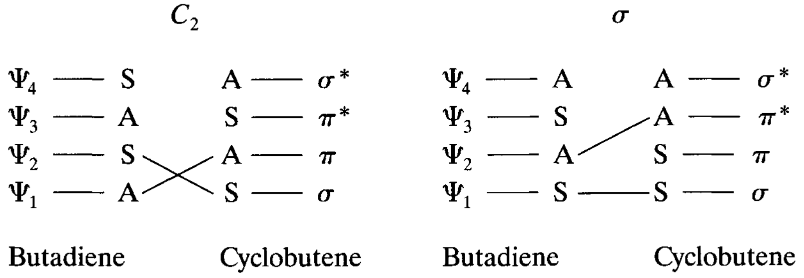


This is a 4π electron process. The bonds involved are the π bonds of the conjugated diene system and the π bond and the ring-forming σ bond of the cyclobutene. The electronic configurations and symmetry characteristics of the orbitals involved are as follows:



Symmetry Correlations between Bonding Orbitals of Starting Materials and Products

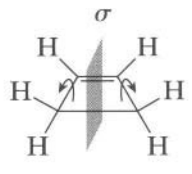
If we examine the classification of orbitals of starting material and product with respect to each of the two symmetry elements in turn, we see that the bonding orbitals, Ψ_1 and Ψ_2, for starting material and product share symmetry only with respect to the C_2 axis. (With respect to the σ plane, both bonding orbitals of the cyclobutene system are symmetric, but in the butadiene system, only Ψ_1 is symmetric with respect to the σ plane.)



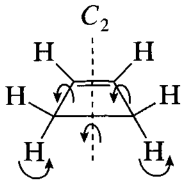
This means that, during the course of a reaction, maximum bonding overlap can be maintained only if all of the intermediates along the reaction pathway also have C_2 symmetry; in other words, the whole process must be symmetrical with respect to C_2. If we look at symmetry correlations with respect to the σ plane, we see that to maintain symmetry with respect to the σ plane, the butadiene orbital Ψ_2 has to correlate with the π^* orbital. This means that in order to maintain symmetry with respect to the σ plane, the reaction would have to form the product in an excited state. The energy requirement for such a conversion would be very large, so that the conversion requiring the correlation of Ψ_2 with π^* would be *symmetry-forbidden.*

Symmetry Characteristics of the Reaction

As we saw in Section 2.B, the interconversion of butadiene and cyclobutene can occur through either a disrotatory or a conrotatory process. As the following diagram shows, the disrotatory opening is symmetrical with respect to a σ plane, whereas conrotatory opening is symmetrical with respect to the C_2 axis.



disrotatory opening

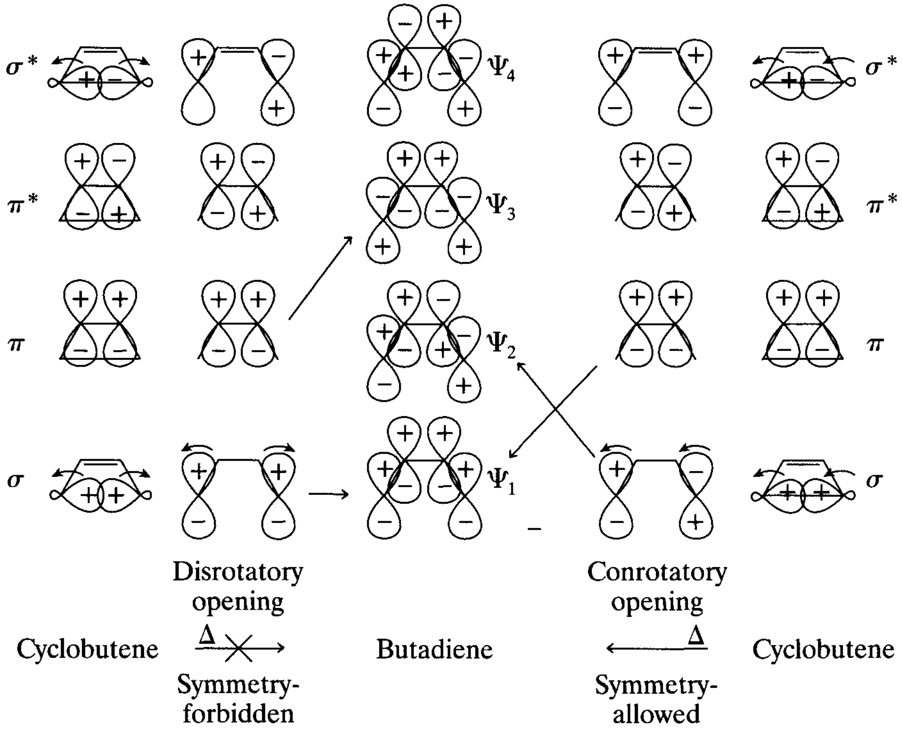


conrotatory opening

Because conrotatory ring opening proceeds so that intermediate structures have C_2 symmetry at all points along the reaction pathway linking starting material and product, it is logical that thermal ring opening of cyclobutene occurs by a conrotatory process. Furthermore, because the disrotatory process does not proceed along a pathway that maintains symmetry, it is not expected to occur.

Orbital Phase Correlations

An alternative way of analyzing the thermal ring-opening reaction is to look at the *phases* of the molecular orbitals involved. These can be visualized as follows:



In conrotatory ring opening, the reoriented σ orbitals derived from cyclobutene look like part of the butadiene molecular orbitals Ψ_2 and Ψ_4. The orbitals derived from the double bond of cyclobutene look like part of the butadiene molecular orbitals Ψ_1 and Ψ_3. Because the signs of the cyclobutene orbitals can be correlated with bonding orbitals of butadiene by conrotatory opening, this mode of ring opening is allowed, whereas disrotatory opening, in which the signs of the cyclobutene orbitals must be correlated with an antibonding orbital, is forbidden.

F. Frontier Orbitals

The frontier orbital approach leads to the same predictions as those based on an analysis of correlation diagrams, but instead of considering all of the orbitals of the π system, only the frontier orbitals, the HOMOs and LUMOs are considered. A general discussion of frontier orbital theory is given in Fukui, K. *Acc. Chem. Res.* **1971**, 57–64. The choice of which HOMOs and LUMOs to combine requires an analysis that we will not undertake here. We will simply show that when these orbitals are combined, we can rationalize reactions observed experimentally in terms of the orbitals derived from this type of analysis.

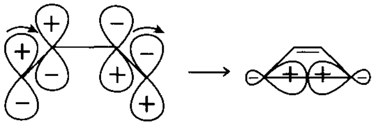
Electrocyclic Reactions

The frontier orbital analysis of electrocyclic reactions focuses on the HOMO of the open-chain polyene.

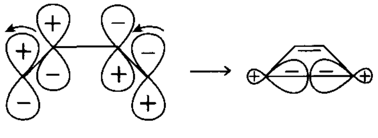
Hint 6.15 In the frontier orbital approach to electrocyclic transformations, the course of reaction is determined by the amplitude of the lobes at the termini of the HOMO of the polyene. Rotation of bonds during reaction will occur in such a way that orbitals of like sign can overlap.

Example 6.23. ***The frontier orbital approach to the thermal ring opening of cyclobutenes.***

The HOMO for butadiene is Ψ_2. In the conrotatory cyclizations shown here, rotation of the lobes at the ends of the HOMO leads to overlap of orbitals with like signs and production of a σ bond.



conrotatory



conrotatory

A disrotatory process, on the other hand, would lead to an antibonding interaction between the ends of the chain and would not lead to formation of the σ bond needed for cyclization.

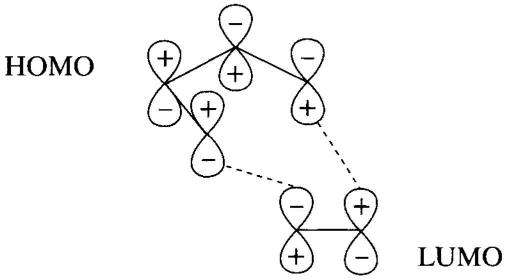
The π bonding orbital of cyclobutene arises from reorganization of the butadiene π system. This process is considered in Woodward, R. B.; Hoffmann, R. *The Conservation of Orbital Symmetry*; Verlag Chemie: Weinheim, 1970; p. 38 ff. and references cited therein.

Cycloaddition

In cycloaddition reactions, frontier orbital analysis considers the interaction of the HOMO of one component and the LUMO of the other.

Example 6.24. ***Frontier orbital overlap in a [4 + 2] cycloaddition.***

In a [4 + 2] cycloaddition, we can consider overlap between the HOMO of the diene and the LUMO of the olefin.

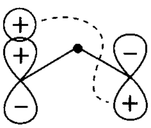


Overlap of lobes with like signs can occur by suprafacial–suprafacial addition or by an antarafacial–antarafacial process. The latter would not be expected for a [4 + 2] reaction because of geometric constraints.

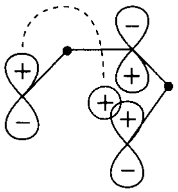
Sigmatropic Rearrangements

Example 6.25. ***Frontier orbital analysis of sigmatropic [1,3] and [1,5] hydrogen shifts.***

We can think of a hydrogen shift as resulting from cleavage of the C—H sigma bond, followed by movement of a hydrogen atom across a π radical system to form a new sigma bond. (Alternative schemes in which a proton moves across a π anion system or a hydride moves across a π cation system would require more energy because these would require separating charges as well as breaking a carbon–hydrogen bond.) For a [1,3] shift, the interacting orbitals that are closest in energy are the 1*s* orbital of hydrogen and the Ψ_2 orbital of the allyl system. Each of these orbitals contains a single electron, unlike the HOMOs involved in electrocyclic reactions and cycloadditions, each of which contains a pair of electrons. In the case of the [1,5] hydrogen shift, the orbitals involved are the 1*s* orbital of hydrogen and the Ψ_3 orbital of the pentadienyl system. We can represent the orbital interactions as follows:



1s + Ψ_2
[1,3] H shift



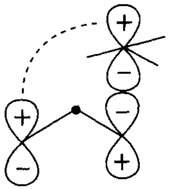
1s + Ψ_3
[1,5] H shift

In the [1,3] shift, a total of 4π electrons are involved. A bonding interaction can be maintained only if the hydrogen moves to the opposite site of the π system (i.e., the rearrangement is antarfacial). Geometry is against this move. Either the hydrogen has to enter a region outside the π system in order to get from one side to the other, or the bond angles of the allyl system have to be strained severely in order for the hydrogen to move from one face to the other while maintaining bonding overlap. Both of these are very high-energy options, so the reaction is not observed.

In the [1,5] shift, 6π electrons are involved. In this case, bonding can be maintained throughout a suprafacial process, and this type of reaction occurs with ease.

Example 6.26. ***Orbitals involved in sigmatropic shifts of carbon.***

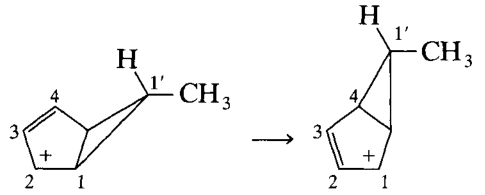
Frontier orbitals can help to explain the results seen when a sigmatropic shift involves migration of carbon rather than hydrogen. A [1,3] migration of carbon involves 4π electrons. We can think of the reaction as migration of a carbon radical across the π system of an allylic radical. In this case, overlap of the *p* orbital of the carbon radical with the allylic π system can be visualized as shown in the following diagram.



Because the p orbital has a node, the carbon atom can move across the π system. As bonding interaction between the + lobes of the p orbital and the π system decreases, interaction develops between the − lobes. In the process, the migrating carbon undergoes inversion analogous to that seen in an S_N2 process. In both cases, the bonds breaking and forming are at a 180° angle.

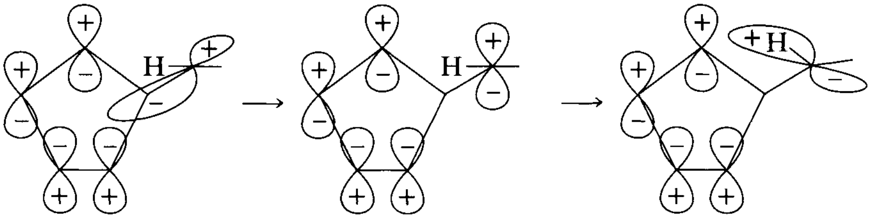
Example 6.27. ***Orbitals involved in sigmatropic shifts in the exo-6-methyl bicyclo[3.1.0]hexenyl cation.***

In this system, as we saw previously, the methyl group remains *exo* as the migration of carbon-6 proceeds around the ring.



As we saw in Example 6.16, this is a [1,4] sigmatropic shift of the carbon labeled 1′ in the equation. (Note that the numbers shown in the equation are not those used to name the compound. Thus, the carbon labeled 1′ for classification of the sigmatropic shift is numbered 6 for the purpose of nomenclature.)

One way to consider the orbital interactions is to think of the process as migration of a carbocation across a butadiene π system. This is a reasonable choice because, in contrast to Example 6.25, the reacting species is already charged. If we consider the reaction as interaction between the LUMO of the carbocation (atomic p orbital) and the HOMO of the butadiene π system (Ψ_2), we can represent the interaction visually as follows:



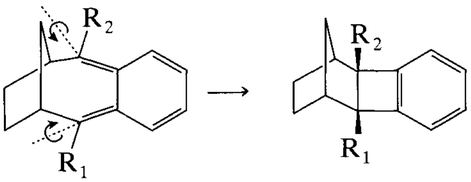
In this scheme, inversion of configuration occurs at C-6, which means that the methyl group remains *exo*. If it is difficult to see that such a transformation leads to the methyl group remaining *exo*, molecular models can be of assistance.

For the actual structures studied see Hart, J.; Rodgers, T. R.; Griffiths, J. *J. Am. Chem. Soc.* **1969**, *91*, 754–756.

ANSWERS TO PROBLEMS

Problem 6.1

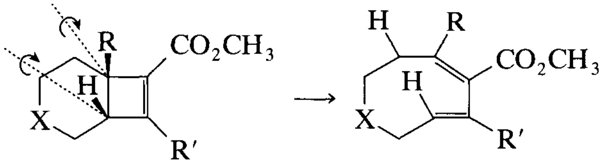
a. For the stereochemistry shown, the process must be disrotatory. This is a four-electron process and, thus, is symmetry-forbidden thermally. The term symmetry-forbidden does not mean the reaction is impossible, merely that so much energy is required that other processes usually occur instead.



This is an example of a symmetry-forbidden reaction that, nonetheless, actually takes place. Failure to conform to the selection rules usually is taken to mean that the reaction proceeds by a nonconcerted mechanism. The electronic effects of the substituents, R_1 and R_2, on the course of the reaction are complex.

b. In order to rotate the substituents into their positions in the product, a conrotatory mode is required. This is a 4π electron process and is thermally allowed. Note that the diene, and not the cyclobutene, is considered in giving the designation and stereochemistry.

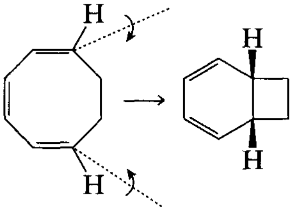
Problem 6.1
continued



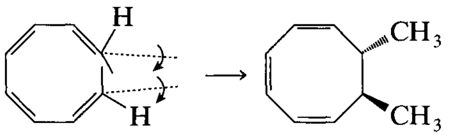
Note the unusual *trans* orientation of the ring carbons across the lower double bond in the product.

Problem 6.2

a. According to Table 6.1, a concerted thermal reaction of a 6π electron system requires a disrotatory mode of ring closing, which leads to a *cis* orientation of the hydrogens.



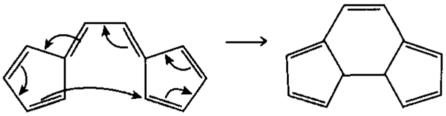
b. To determine the stereochemical consequences of the reaction, first rotate about the single bonds of the starting material to get a conformation in which the ends of the tetraene system are close enough to react. These rotations change the conformation of the molecule, but not the stereochemistry. Note, however, that you may *not* rotate about any of the double bonds to get the ends into position because that would change the stereochemistry of the tetraene. All of the double bonds have *cis* stereochemistry. Because this is an 8π electron system, the thermally allowed process will be conrotatory. Conrotatory rotation gives the product with the two methyl groups *trans*.



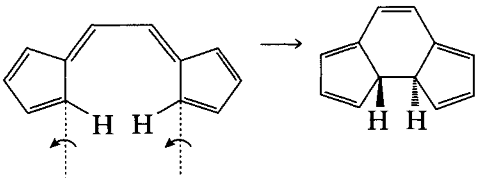
c. As in the previous example, the starting material must be placed in a conformation in which the ends of the π system are close enough to react.

Problem 6.2 *continued*

If it is not clear to you which electrons are necessary for the transformation, drawing arrows for the redistribution of electrons can be helpful.

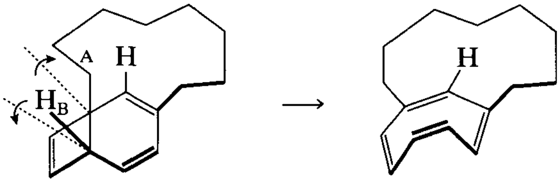


In order to get the product, all 12π electrons must be involved. Thus, the thermal reaction should be conrotatory, and the hydrogens will be *trans*.



Problem 6.3

To obtain the stereochemistry observed in the product the long chain (carbon A) must move behind the plane of the page and hydrogen B (H_B) must move in front of the plane of the page. This is a disrotatory process.



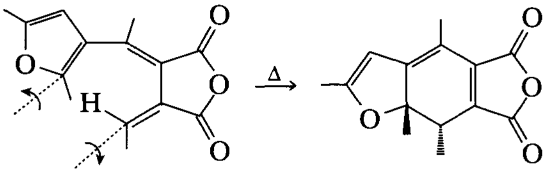
We can consider the change from starting material to product as involving either 4π electrons or 6π electrons, depending on whether we consider the process to be the ring opening of a four-membered ring or a six-membered ring. If it is a 4π-electron process, disrotatory opening can

Problem 6.3 *continued*

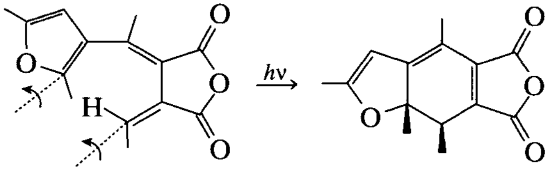
occur only under photochemical conditions. If the reaction is a 6π-electron process, its is symmetry allowed under thermal conditions.

Problem 6.4

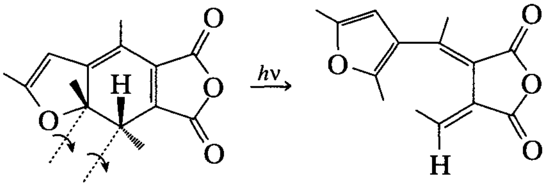
a. The thermal reaction will be disrotatory, leading to *trans*-methyl groups:



b. This is a 6π electron process. (Only one of the π bonds in the furan ring is involved in the reaction.) The photochemical reaction will be conrotatory (antarafacial), leading to *cis*-methyl groups:

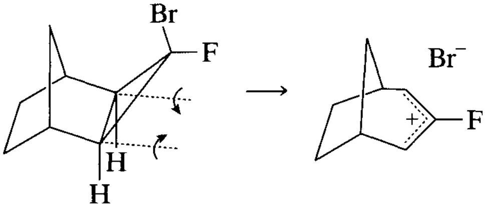


c. The photochemical ring opening of the thermal product will be conrotatory. (Remember, the total number of electrons counted in a process is that of the open-chain compound.) Thus, the product will be an isomer of the starting material for the original process.



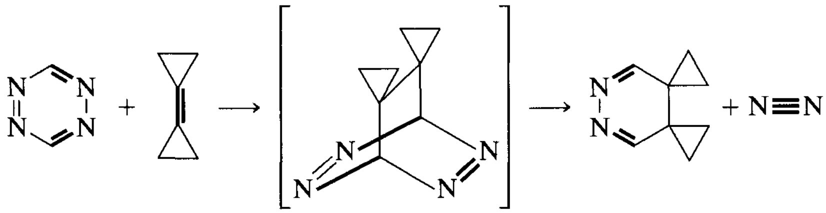
Problem 6.5

Ionization occurs to a 2π electron allylic cation. To be thermally allowed, therefore, the motion must be disrotatory. Only the disrotatory motion, which moves the hydrogens outward, will occur. This places the developing *p* orbitals opposite the bromide leaving group only for the second compound. The bromide ion then reacts with the cation to produce the product. In the first compound, the developing *p* orbitals will be opposite the fluoride group, which is such a poor leaving group that no reaction occurs.



Problem 6.6

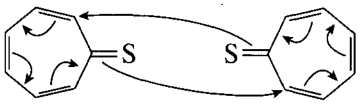
a. Both the cycloaddition to give the intermediate and the cycloreversion of the intermediate to give the product are [4 + 2] reactions. The electrons involved in each process are highlighted in the following structures:



In the retrocycloaddition, only two of the π electrons of the N_2 product are used. The other two π electrons are perpendicular (orthogonal) to the first two and cannot take place in the reaction. Thus, by considering the products of the reaction, this is a $[\pi_s^4 + \pi_s^2]$ process. On the other hand, the reaction of the intermediate would be designated as a $[\sigma_s^2 + \sigma_s^2 + \pi_s^2]$ process.

Problem 6.6 *continued*

b. This is an [8 + 8] cycloaddition, as becomes evident when arrows are used to show the flow of electrons leading to product. Because this is a $4n$ cycloaddition, the selection rules dictate a supra–antara cyclization, which is equivalent to a concerted *trans* addition. This is difficult to visualize. It is easier to visualize the supra–supra cyclization, which would lead to the isomer in which the hydrogen atoms are *trans*. From this we can conclude that because the product has the two hydrogens *cis*, the reaction must be supra–antara or antara–supra.



c. This is a [6 + 4] addition. The π electrons of the carbonyl are not involved. The selection rules predict a supra–supra or antara–antara process, which results in the observed *cis* stereochemistry.

d. The singlet oxygen has all electrons paired and so reacts as the two-electron component of a [4 + 2] addition. In the more commonly encountered triplet state, oxygen has two unpaired electrons and reacts as a diradical.

Problem 6.7

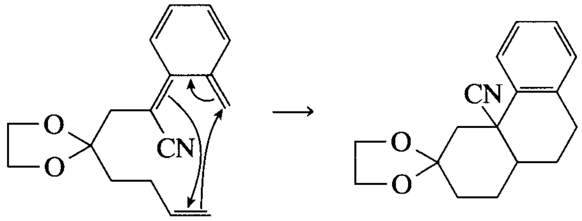
a. $[\pi_s^4 + \pi_s^2]$. The phenyls of the diene and the carbonyls of the heterocycle are not involved in the ring-forming process, so the π electrons in these substituents are not counted. The two hydrogens, which are shown up (*cis*) in the product, also are *cis* in the starting material. In addition, the two phenyl groups of the diene end up on the same side of the six-membered ring. Both of these stereochemical consequences are the result of suprafacial processes. This can be demonstrated readily by using models.

b. $[\pi_s^2 + \pi_s^2]$. The best way to understand the stereochemistry of the process is to look at models. Placing the appropriate termini together in a model of the starting material shows that the stereochemistry of the product is produced when both components react suprafacially. The π electrons of the C=O group and the dimethoxy-substituted π bond are not counted because they are not involved in the reaction. This is a thermal reaction, so that a nonconcerted pathway is expected.

Problem 6.8

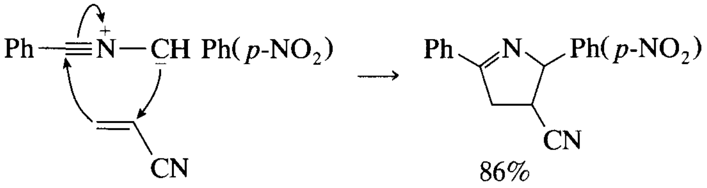
$[\pi^4 + \pi^4]$. The nitrone component contains four electrons: the two π electrons of the double bond and the two π electrons on the oxygen that overlap with them. The diene component also contains four electrons. The nitrone component contains three atoms and the diene component contains four atoms, so that a [4 + 3] adduct is formed. The authors cited propose that this adduct is formed by a diradical mechanism. For more on this reaction, see Problem 7.2.b.

Problem 6.9

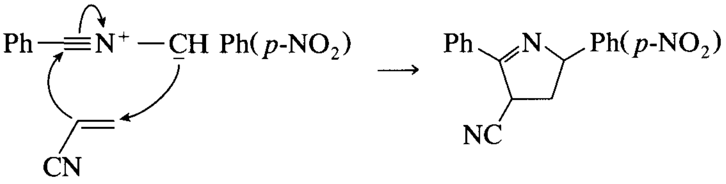


Problem 6.10

The following reaction shows the actual regiochemistry observed:



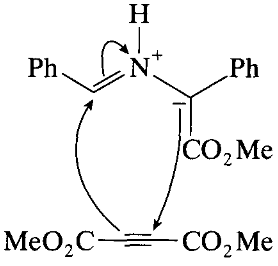
Because the double bond is polarized by the nitrile group, we might have expected the following reaction to predominate:



As indicated in the text, many of these reactions show high regioselectivity. However, it is not possible to predict this regiochemistry without molecular orbital calculations.

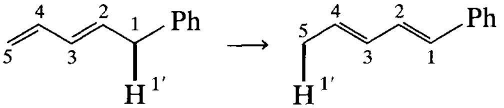
Problem 6.11

A possible mechanism is intermolecular proton transfer from one molecule of the starting ester–imine to another to give a 1,3-dipole, which then cycloadds to the acetylene.



Problem 6.12

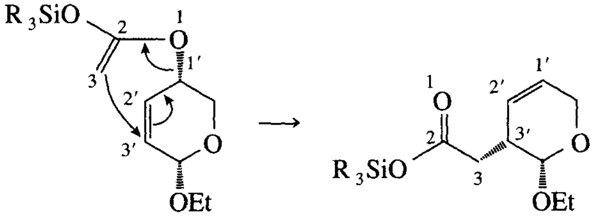
a. This is a [1,5] sigmatropic shift. The highlighted σ bond has been broken, the π system has shifted, and a new σ bond has been formed at the other end of the π system. Numbering atoms from each end of the original σ bond through the terminal atoms of the new σ bond gives the following:



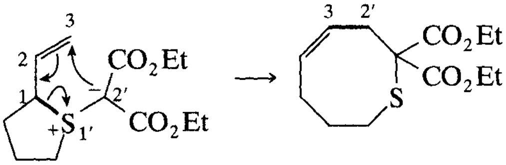
Thus, the hydrogen has moved from the 1 position to the 5 position on the chain. The 1 in the designation [1,5] indicates that at one end of the new σ bond is an atom (the hydrogen) that also was at one end of the old σ bond. The 5 indicates that the other end of the new σ bond is formed at the 5 position along the carbon chain, atom number 5.

b. This is a [3,3] sigmatropic shift. It is an example of the Claisen rearrangement, a [3,3] sigmatropic rearrangement of a vinyl ether.

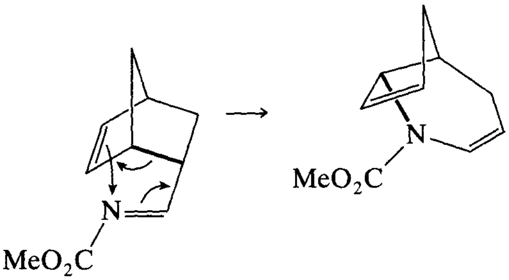
Problem 6.12
continued



c. [2,3]

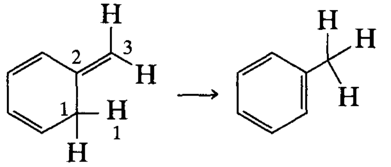


d. This is a [3,3] sigmatropic shift. It is an example of the Cope rearrangement, in which one of the carbons has been replaced by nitrogen. The σ bond broken and the new σ bond formed are highlighted in the structures.



Problem 6.13

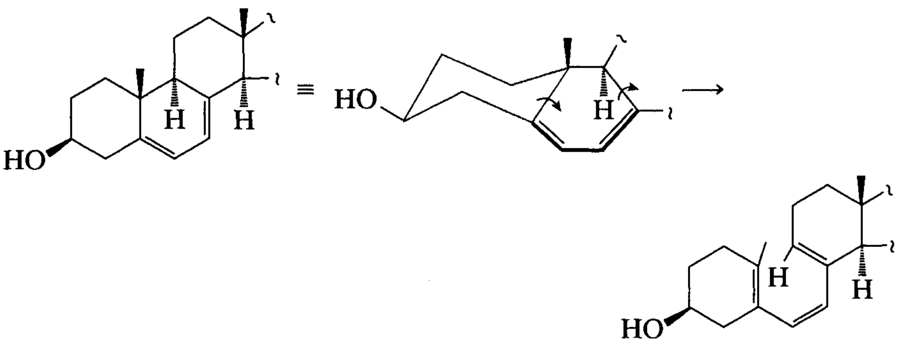
Rearrangement to the aromatic toluene requires a [1,3] sigmatropic shift of hydrogen.



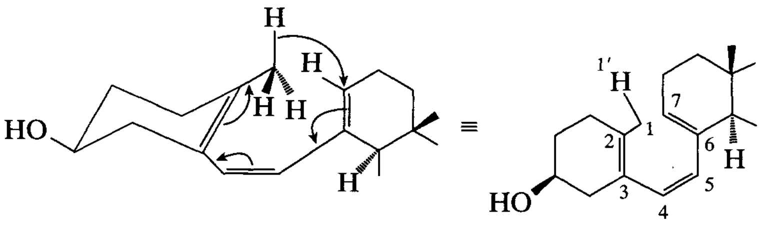
A suprafacial shift does not obey the selection rules and the geometry required makes an antarafacial shift very difficult, so that the compound is kinetically stable. The activation energy for rearrangement is large enough that the compound can be isolated even though it is thermodynamically unstable, just like diamond, which is kinetically stable even though it is thermodynamically unstable compared to graphite.

Problem 6.14

The photochemical transformation is a 6π electron ($4n + 2$) electrocyclic ring opening. The selection rules predict a conrotatory process as illustrated:



The alternative conrotatory opening would not be possible because it would result in the formation of *trans* double bonds in both cyclohexene rings. The second reaction is a thermal [1,7] sigmatropic hydrogen shift.

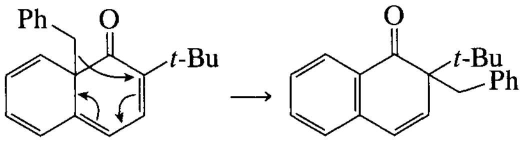


Problem 6.14 *continued*

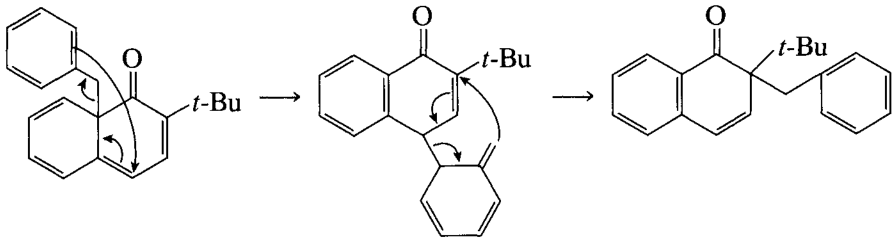
The selection rules predict an antarafacial process. In this case, suprafacial and antarafacial processes would lead to the same product.

Problem 6.15

a. This rearrangement could take place by two different mechanisms. One is a [1,5] sigmatropic shift to give the product directly:

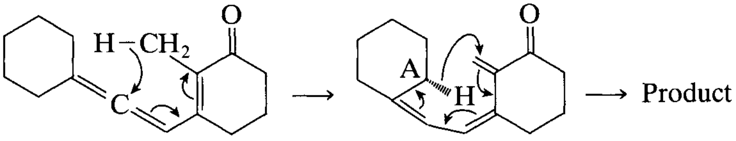


The other is two sequential [3,3] sigmatropic shifts:



The authors of the paper cited favor the [1,5] rearrangement because direct formation of the product is thermodynamically more favorable than proceeding through the intermediate from the first [3,3] sigmatropic shift.

b. This transformation was described by the authors cited as a [1,5] shift, followed by a "spontaneous" [1,7] shift.

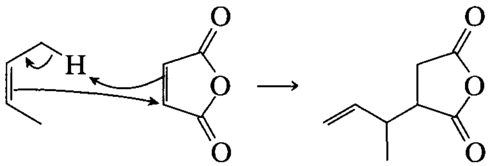


6-20

Problem 6.15
continued

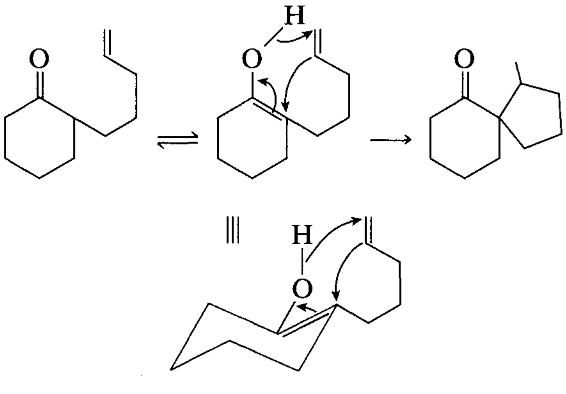
The [1,5] shift would be a suprafacial reaction. The [1,7] shift must be antarafacial in the π component to be thermally allowed. The proton, located at carbon A in **6-20**, moves from the bottom side of the six-membered ring to the top side of the π system at the other end. In general, the antarafacial process, necessary for a thermal [1,7] sigmatropic shift, occurs with ease, especially when compared to the antarafacial process that would be required for a thermal [1,3] sigmatropic shift.

Problem 6.16

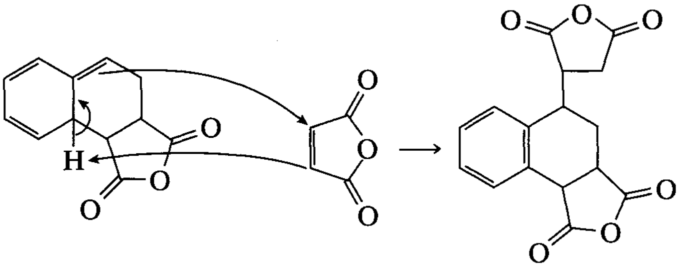


Problem 6.17

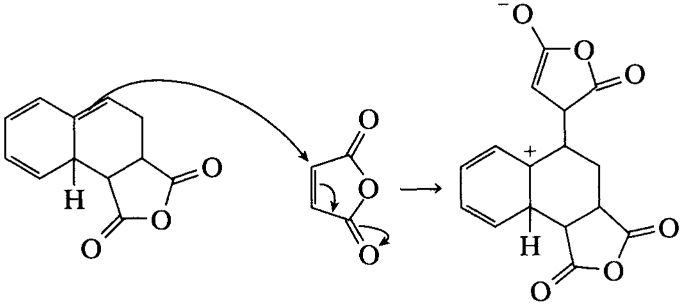
The mechanism can be written as an ene cyclization if we write the enol form of the keto group.



Problem 6.18 a. The major pathway, a $[\pi_s^2 + \pi_s^2 + \sigma_s^2]$ reaction, is an ene reaction.



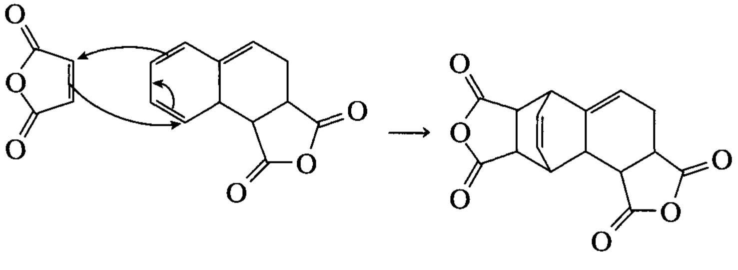
A stepwise mechanism also could be written for this reaction:



6-21

The intermediate formed, initially, **6-21**, is both an acid and a base. Appropriate intermolecular acid–base reactions, followed by tautomerization, can generate the product readily.

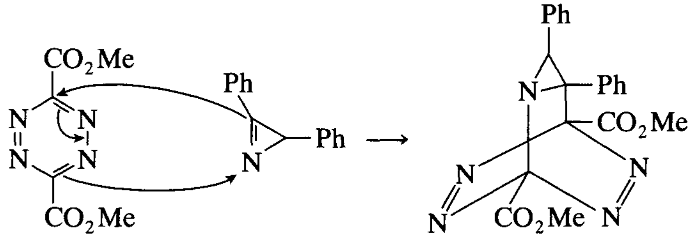
The minor product, formed in 11% yield, results from a Diels–Alder reaction, a $[\pi_s^4 + \pi_s^2]$ cycloaddition.



Miller, Audrey, et al. Writing Reaction Mechanisms in Organic Chemistry, Elsevier Science & Technology, 1999. ProQuest Ebook Central, http://ebookcentral.proquest.com/lib/inflibnet-ebooks/detail.action?docID=299474.

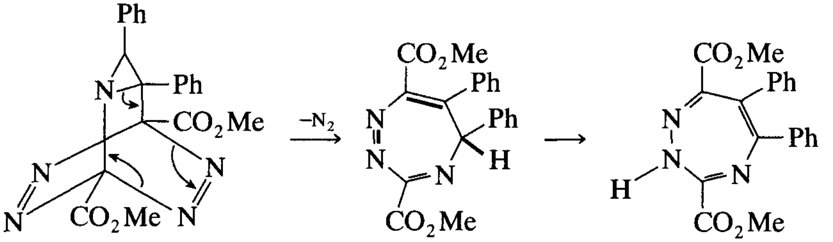
Problem 6.18
continued

b. The first step is a $[\pi_s^4 + \pi_s^2]$ cycloaddition to give **6-22**.



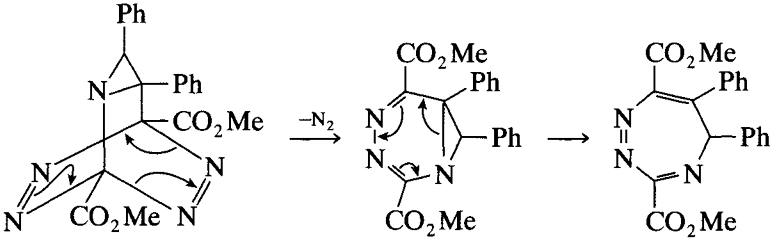
6-22

The second step is a retrocycloaddition to give nitrogen and **6-23**, a $[\pi_s^4 + \pi_s^2]$ process. Finally, **6-23** undergoes a [1,5] sigmatropic shift to form the final product. In **6-23**, the bonds involved in the sigmatropic shift are highlighted.



6-22 **6-23**

Another possible decomposition of **6-22**, $[\pi_s^4 + \pi_s^2]$, could give **6-24**, which then could open in a 6π electron electrocyclic reaction to give **6-23**.

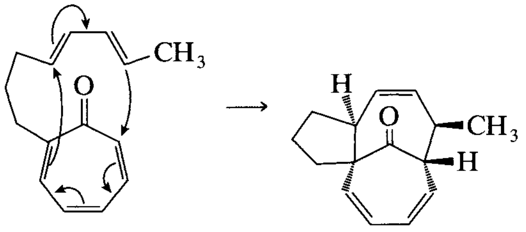


6-22 **6-24** **6-23**

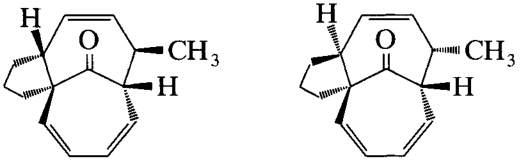
Problem 6.18
continued

The direct opening of **6-22** to **6-23** appears more favorable, on the basis of immediate relief of the strain of the three-membered ring.

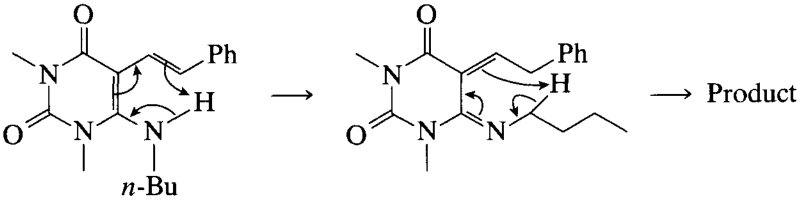
c. This reaction is a [$\pi_s^6 + \pi_s^4$] intramolecular cycloaddition. The paper cited noted that the reaction is "periselective"; that is, none of the [4 + 2] cycloadduct is produced.



The two alternative [$\pi_a^6 + \pi_a^4$] modes of reaction are extremely unlikely, because they give products with very high strain energy.

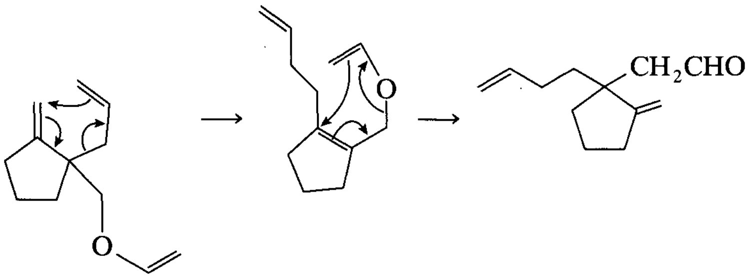


d. The product can be explained as the result of two consecutive [1,5] sigmatropic shifts.



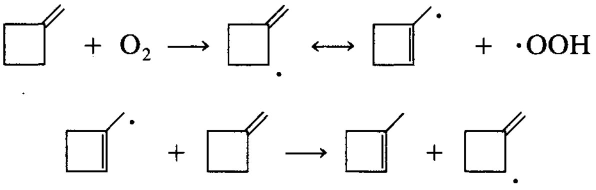
Problem 6.18
continued

e. The product can be produced by two consecutive [3,3] sigmatropic shifts.

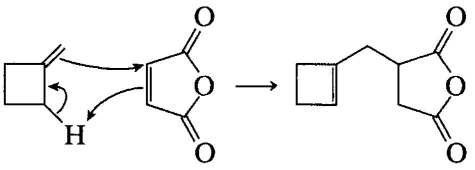


The first reaction is a Cope rearrangement, and the second reaction, rearrangement of a vinyl ether, is a Claisen rearrangement.

f. Step a looks like a [1,3] sigmatropic shift. However, because a concerted shift would have to be a antarafacial-suprafacial reaction, which is unfavorable sterically, the mechanism probably is not concerted. A radical chain reaction, initiated by a small amount of peroxide or oxygen, is possible.



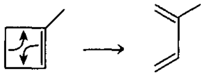
Step b is the ene reaction.



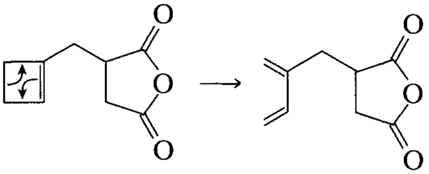
Problem 6.18
continued

Steps c and d are electrocyclic ring opening ($[\pi_a^4]$) processes. Because there are only hydrogens on the sp^3-hybridized carbons of the cyclobutene rings, there is no way to observe the stereochemical consequences of ring opening. Therefore, the arrows shown indicate only the rearrangement of electrons.

Step c:



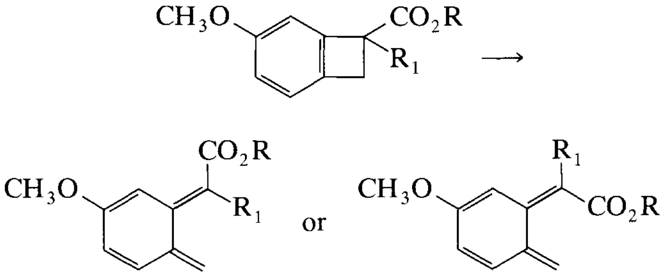
Step d:



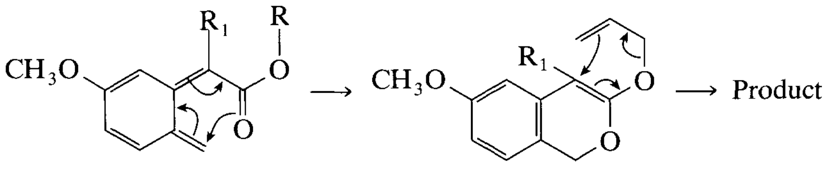
Steps e and f are $[\pi_s^4 + \pi_s^2]$ cycloadditions.

Problem 6.19

In the following equations, R is the allyl group. The first step, electrocyclic ring opening of the four-membered ring, is very common for benzocyclobutenes. There are two possible products for this ring opening (each from a possible conrotatory mode), but only **6-25** has the correct orientation to continue the reaction. The next two steps are both [3,3] sigmatropic shifts.



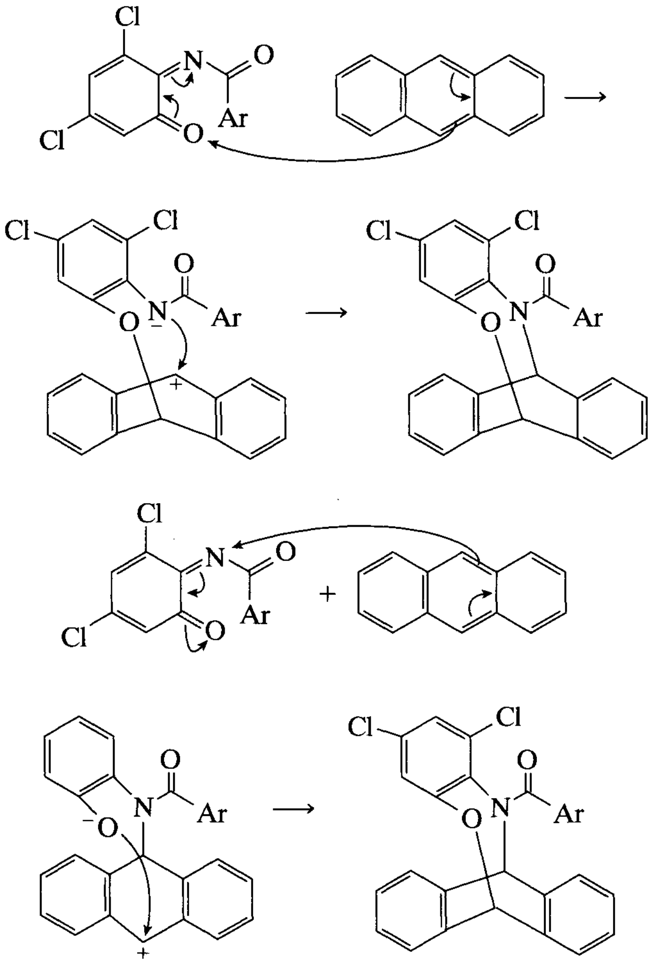
6-25



6-25

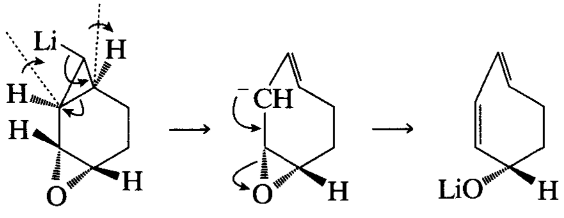
Problem 6.20

The fact that the reaction occurs readily suggests that it is not concerted, because a [$\pi_s^4 + \pi_s^4$] reaction is not a thermally allowed process (see Table 6.2). Whereas the stereochemistry of the product shows that anthracene has reacted suprafacially, the presence of oxygen and nitrogen at the ends of the other 4π electron component precludes a determination of the stereochemistry of addition at this component. However, antarafacial reaction of this component is unlikely because it would require a large amount of twist in the transition state. Thus, this transformation probably proceeds through an intermediate, which is likely to be charged. A positive charge could be stabilized by conjugation with two aromatic rings of the anthracene component. A negative charge could be stabilized by N and/or O, as well as by the electron-withdrawing chlorines. Therefore, reaction of anthracene on either oxygen or nitrogen gives a stabilized intermediate:



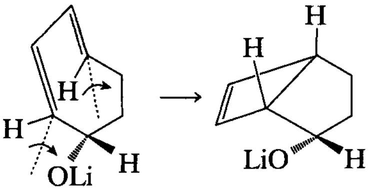
Problem 6.21

a. The first ring opening is a conrotatory process typical of a 4π electron thermal reaction. That is, in **6-26** there are an anion and a π bond giving a total of four electrons:



6-26 **6-17**

Formation of **6-19** follows from conrotatory ring closure of the heptadiene:

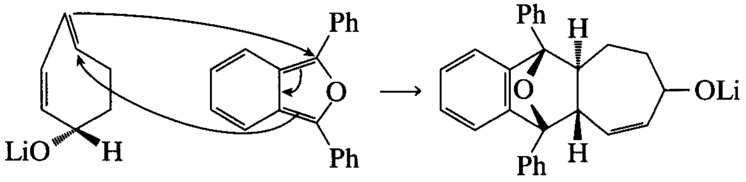


6-19

Notice that the conrotatory motion moves the hydrogens up and the carbons down. Ring closure to form **6-19** is favored because of the ring strain associated with a *trans* double bond in a seven-membered ring.

The isobenzofuran acts as a 4π electron component in a [4 + 2] cycloaddition to trap the intermediate. As usual, both components must react suprafacially. Thus, because the fusion between the six- and seven-membered rings in **6-18** is *trans*, it must be the *trans* double bond in **6-16** that reacts in this trapping reaction.

Problem 6.21
continued



6-18

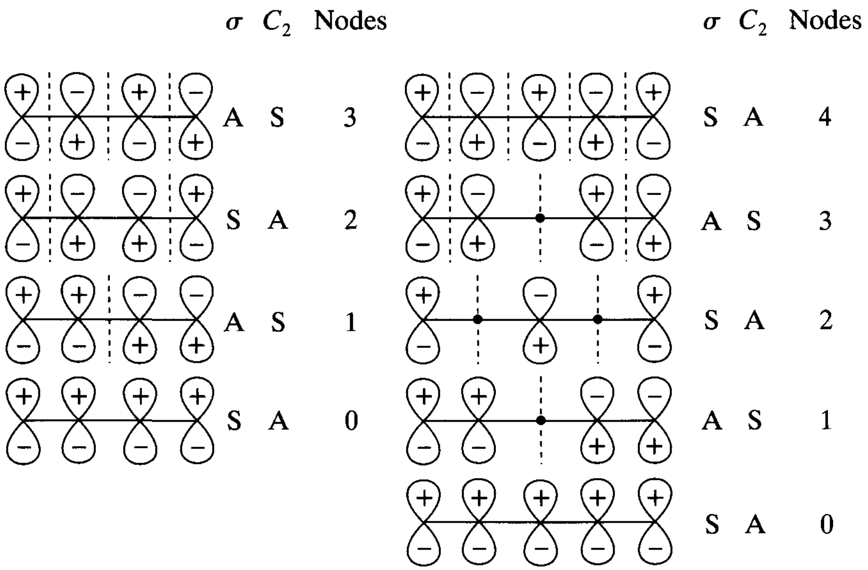
Problem 6.22

The single node should be located symmetrically, that is, at the center of the system. Because the node is located incorrectly, the orbital is neither symmetric nor antisymmetric.

Problem 6.23

The lowest energy orbital shown has no nodes, but the next higher one has two nodes. There should be an MO of intermediate energy with one node. In addition, the orbitals do not alternate in symmetry. Both of the orbitals have the same symmetry with respect to the σ plane (S) and the C_2 axis (A).

Problem 6.24



Problem 6.24
continued

Some of the nodes coincide with nuclei in the five-carbon π system because the nodes must be placed symmetrically with respect to the mirror plane that bisects the system.

Problem 6.25

The pentadienyl cation has 4π electrons; the radical and the anion have 5π and 6π electrons, respectively. To obtain the electronic configuration, fill in the MOs in order, starting with the orbital of lowest energy.