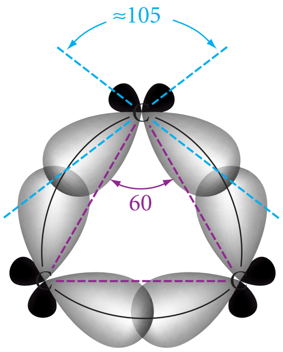


Figure 7.12 The orbitals that overlap to form each C—C bond in cyclopropane do not lie along the straight line between the carbon atoms. These carbon–carbon bonds (*black lines*) are sometimes called "bent" or "banana" bonds. The C—C—C angle is 60° (*purple dashed lines*), but the angles between the orbitals on each carbon are closer to 105° (*blue dashed lines*).

Because three carbons define a plane, the carbon skeleton of cyclopropane is planar; thus, neither its angle strain nor the eclipsing interactions between its hydrogens can be relieved by puckering. As the data in Table 7.1 show, cyclopropane is the least stable of the cyclic alkanes. The carbon–carbon bonds of cyclopropane are bent in a "banana" shape around the periphery of the ring. Such "bent bonds" allow for angles between the carbon orbitals that are on the order of 105°, closer to the ideal tetrahedral value of 109.5° (Fig. 7.12). Although bent bonds reduce angle strain, they do so at a cost of less effective overlap between the carbon orbitals.

Further Exploration 7.2
Alkenelike Behavior of Cyclopropanes

PROBLEMS

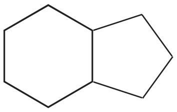
7.15 (a) The dipole moment of *trans*-1,3-dibromocyclobutane is 1.1 D. Explain why a nonzero dipole moment supports a puckered structure rather than a planar structure for this compound.
(b) Draw a structure for the more stable conformation of *trans*-1,2-dimethylcyclobutane.

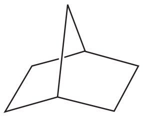
7.16 Tell whether each of the following compounds is chiral.
(a) *cis*-1,2-dimethylcyclopropane
(b) *trans*-1,2-dimethylcyclopropane

7.6 BICYCLIC AND POLYCYCLIC COMPOUNDS

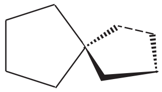
A. Classification and Nomenclature

Some cyclic compounds contain more than one ring. If two rings share two or more common atoms, the compound is called a **bicyclic compound.** If two rings have a single common atom, the compound is called a **spirocyclic compound.**

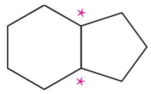

bicyclo[4.3.0]nonane


bicyclo[2.2.1]heptane

(bicyclic compounds)


spiro[4.4]nonane
(a spirocyclic compound)

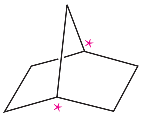
The atoms at which two rings are joined in a bicyclic compound are called **bridgehead carbons.** Bicyclic compounds are further classified according to the relationship of the bridgehead carbons. When the bridgehead carbons of a bicyclic compound are adjacent, the compound is classified as a **fused bicyclic compound:**



bridgehead carbons (*) at adjacent positions

a fused bicyclic compound

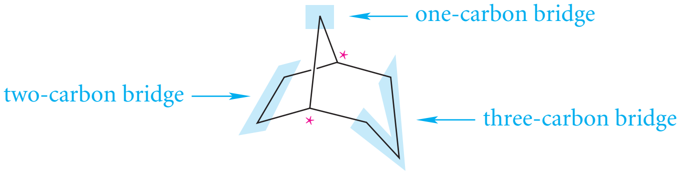
When the bridgehead carbons are not adjacent, the compound is classified as a **bridged bicyclic compound:**



bridgehead carbons (*) not adjacent

a bridged bicyclic compound

The nomenclature of bicyclic hydrocarbons is best illustrated by example:

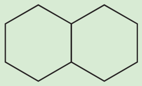


bicyclo[3.2.1]octane
(* = bridgehead carbons)

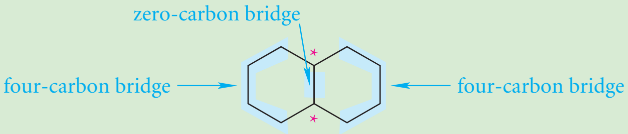
This compound is named as a bicyclooctane because it is a bicyclic compound containing a total of eight carbon atoms. The numbers in brackets represent the number of carbon atoms in the respective bridges, in order of decreasing size.

Study Problem 7.4

Give the IUPAC name of the following compound. (Its common name is *decalin.*)



Solution The compound has two fused rings that contain a total of 10 carbons, and is therefore named as a bicyclodecane. Three bridges connect the bridgehead carbons: two contain four carbons, and *one contains zero carbons*. (The bond connecting the bridgehead carbons in a fused-ring system is considered to be a bridge with zero carbons.)



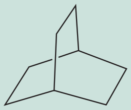
bicyclo[4.4.0]decane
(* = bridgehead carbons)

The compound is named bicyclo[4.4.0]decane.

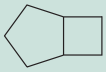
PROBLEMS

7.17 Name the following compounds:

(a)



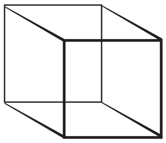
(b)



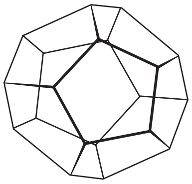
7.18 Without drawing their structures, tell which of the following compounds is a fused bicyclic compound and which is a bridged bicyclic compound, and how you know.

bicyclo[2.1.1]hexane (*A*) bicyclo[3.1.0]hexane (*B*)

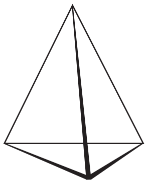
Some organic compounds contain many rings joined at common atoms; these compounds are called **polycyclic compounds.** Among the more intriguing polycyclic compounds are those that have the shapes of regular geometric solids. Three of the more spectacular examples are cubane, dodecahedrane, and tetrahedrane.



cubane



dodecahedrane

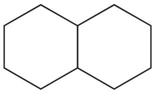


tetrahedrane

Cubane, which contains eight —CH— groups at the corners of a cube, was first synthesized in 1964 by Professor Philip Eaton and his associate Thomas W. Cole at the University of Chicago. Dodecahedrane, in which 20 —CH— groups occupy the corners of a dodecahedron, was synthesized in 1982 by a team of organic chemists led by Professor Leo Paquette of the Ohio State University. Tetrahedrane itself has not yielded to synthesis, although a derivative containing *tert*-butyl substituent groups at each corner has been prepared. Chemists tackle the syntheses of these very pretty molecules not only because they represent interesting problems in chemical bonding, but also because of the sheer challenges of the endeavors.

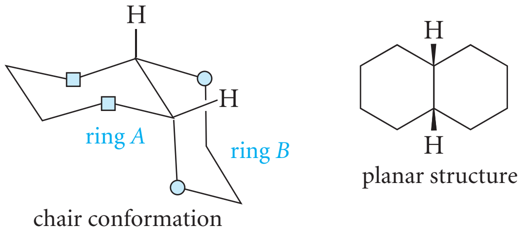
B. Cis and Trans Ring Fusion

Two rings in a fused bicyclic compound can be joined in more than one way. Consider, for example, bicyclo[4.4.0]decane, which has the common name *decalin*.



decalin
(bicyclo[4.4.0]decane)

There are two stereoisomers of decalin. In *cis*-decalin, two —CH_2— groups of ring *B* (circles) are cis substituents on ring *A*; likewise, two —CH_2— groups of ring *A* (squares) are cis substituents on ring *B*.

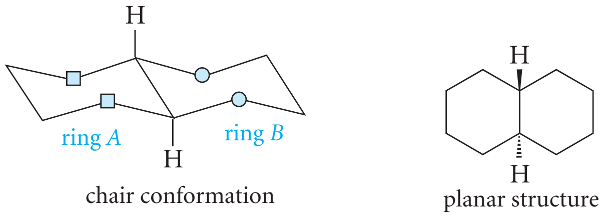


(7.25)

***cis*-decalin**

The cis ring fusion can be shown in a planar structure by showing the cis arrangements of the bridgehead hydrogens.

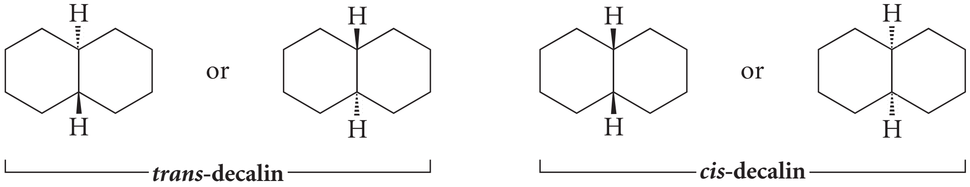
In *trans*-decalin, the —CH_2— groups adjacent to the ring fusion are in a trans-diequatorial arrangement. The bridgehead hydrogens are trans-diaxial.



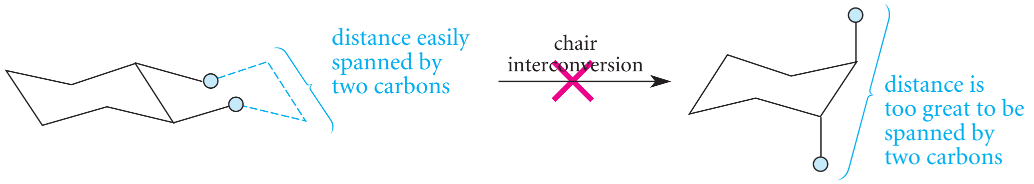
(7.26a)

***trans*-decalin**

Both *cis*- and *trans*-decalin have two equivalent planar structures:



Each cyclohexane ring in *cis*-decalin can undergo the chair interconversion. You should verify with models that when one ring changes its conformation, the other must change also. However, in *trans*-decalin, the six-membered rings can assume twist-boat conformations, but they cannot change into their alternative chair conformations. You should try the chair interconversion with a model of *trans*-decalin to see for yourself the validity of this point. Focus on ring *B* of the *trans*-decalin structure in Eq. 7.26a. Notice that the two circles represent carbons that are in effect *equatorial* substituents on ring *A*. If ring *A* were to convert into the other chair conformation, these two carbons in ring *B* would have to assume *axial* positions, because, in the chair interconversion, equatorial groups become axial groups. When these two carbons are in axial positions, they are much farther apart than they are in equatorial positions; the distance between them is simply too great to be spanned easily by the remaining two carbons of ring *B*.



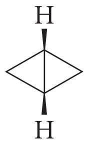
(7.26b)

As a result, the chair interconversion introduces so much ring strain into ring *B* that the interconversion cannot occur. Exactly the same problem occurs with ring *A* when ring *B* undergoes the chair interconversion.

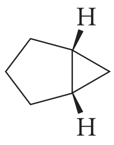
PROBLEM

7.19 How many 1,3-diaxial interactions occur in *cis*-decalin? In *trans*-decalin? Which compound has the lower energy and by how much? (*Hint:* Use your models, and don't count the same 1,3-diaxial interaction twice.)

Trans-decalin is more stable than *cis*-decalin because it has fewer 1,3-diaxial interactions (Problem 7.19). Trans ring fusion, however, is not the more stable way of joining rings in all fused bicyclic molecules. In fact, if both of the rings are small, trans ring fusion is virtually impossible. For example, only the cis isomers of the following two compounds are known:



bicyclo[1.1.0]butane



bicyclo[3.1.0]hexane

Attempting to join two small rings with a trans ring junction introduces too much ring strain. The best way to see this is with models, using the following exercise as your guide.

PROBLEM

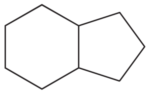
7.20 **(a)** Compare the difficulty of making models of the cis and trans isomers of bicyclo[3.1.0]hexane. (Don't break your models!) Which is easier to make? Why?

(b) Compare the difficulty of making models of *trans*-bicyclo[3.1.0]hexane and *trans*-bicyclo[5.3.0]decane. Which is easier to make? Explain.

In summary:

1. Two rings can in principle be fused in a cis or trans arrangement.
2. When the rings are small, only cis fusion is observed because trans fusion introduces too much ring strain.
3. In larger rings, both cis- and trans-fused isomers are well known, but the trans-fused ones are more stable because 1,3-diaxial interactions are minimized (as in the decalins).

Effects (2) and (3) are about equally balanced in the *hydrindanes* (bicyclo[4.3.0]nonanes); heats of combustion show that the trans isomer is only 4.46 kJ mol^{-1} (1.06 kcal mol^{-1}) more stable than the cis isomer.

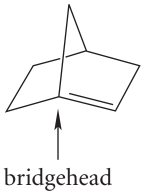


hydrindane
(bicyclo[4.3.0]nonane)

C. *Trans*-Cycloalkenes and Bredt's Rule

Cyclohexene and other cycloalkenes with small rings have cis (or *Z*) stereochemistry at the double bond. Is there a *trans*-cyclohexene? The answer is that the *trans*-cycloalkenes with six or fewer carbons have never been observed. The reason becomes obvious if you try to build a model of *trans*-cyclohexene. In this molecule the carbons attached to the double bond are so far apart that it is difficult to connect them with only two other carbon atoms. To do so either introduces a great amount of strain, or requires twisting the molecule about the double bond, thus weakening the overlap of the 2*p* orbitals involved in the π bond. *Trans*-cyclooctene is the smallest *trans*-cycloalkene that can be isolated under ordinary conditions; however, it is 47.7 kJ mol^{-1} (11.4 kcal mol^{-1}) less stable than its cis isomer.

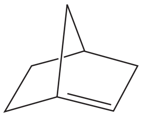
Closely related to the instability of *trans*-cycloalkenes is the instability of any small bridged bicyclic compound that has a double bond at a bridgehead atom. The following compound, for example, is very unstable and has never been isolated:



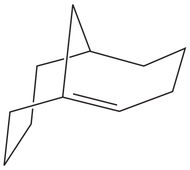
bicyclo[2.2.1]hept-1(2)-ene
(unknown)

The instability of compounds with bridgehead double bonds has been generalized as **Bredt's rule:** *In a bicyclic compound, a bridgehead atom contained solely within small rings cannot be part of a double bond*. (A "small ring," for purposes of Bredt's rule, contains seven or fewer atoms within the ring.)

The basis of Bredt's rule is that double bonds at bridgehead carbons within small rings are twisted; that is, the atoms directly attached to such double bonds *cannot* lie in the same plane. To see this, try to construct a model of bicyclo[2.2.1]hept-1(2)-ene, the bicyclic alkene shown above. You will see that the bicyclic ring system cannot be completed without twisting the double bond. This is similar to the double-bond twisting that would occur in *trans*-cyclohexene. Like the corresponding *trans*-cycloalkenes, bicyclic compounds containing bridgehead double bonds solely within small rings are too unstable to isolate. Bicyclic compounds that have bridgehead double bonds within larger rings are more stable and can be isolated.



bicyclo[2.2.1]hept-1(2)-ene
too unstable to isolate

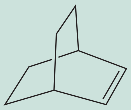


bicyclo[4.4.1]undec-1(2)-ene
stable enough to isolate

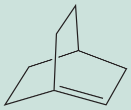
PROBLEM

7.21 Use models if necessary to help you decide which compound within each pair should have the greater heat of formation. Explain.

(a)

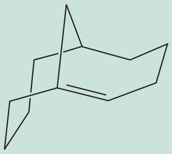


A

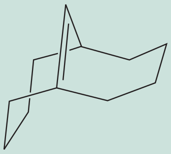


B

(b)



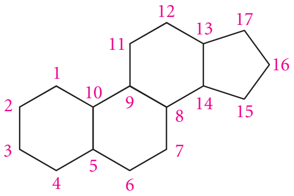
A



B

D. Steroids

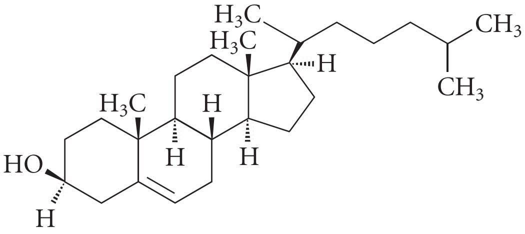
Of the many naturally occurring compounds with fused rings, the *steroids* are particularly important. A **steroid** is a compound with a structure derived from the following tetracyclic ring system:



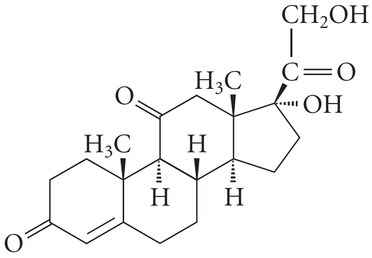
Steroids have a special numbering system, which is shown in the preceding structure. The various steroids differ in the functional groups that are present on this carbon skeleton.

Two structural features are particularly common in naturally occurring steroids, (Fig. 7.13). The first is that in many cases all ring fusions are trans. Because trans-fused cyclohexane rings cannot undergo the chair interconversion (see Eq. 7.26b and subsequent discussion), all-trans ring fusion causes a steroid to be conformationally rigid and relatively flat. This can be seen particularly with the models in Figs. 7.13c–d. Second, many steroids have methyl groups, called *angular methyls,* at carbons 10 and 13. The hydrogens of these methyl groups are shown in color in Figs. 7.13c–d.

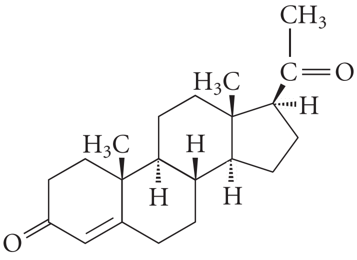
Many important hormones and other natural products are steroids. Cholesterol occurs widely and was the first steroid to be discovered (1775). The corticosteroids and the sex hormones represent two biologically important classes of steroid hormones.



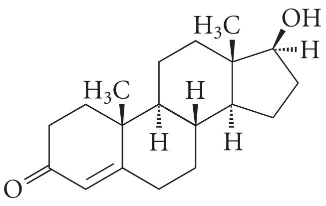
cholesterol
(important component of membranes:
principal component of gallstones;
major constituent of atherosclerotic plaques)



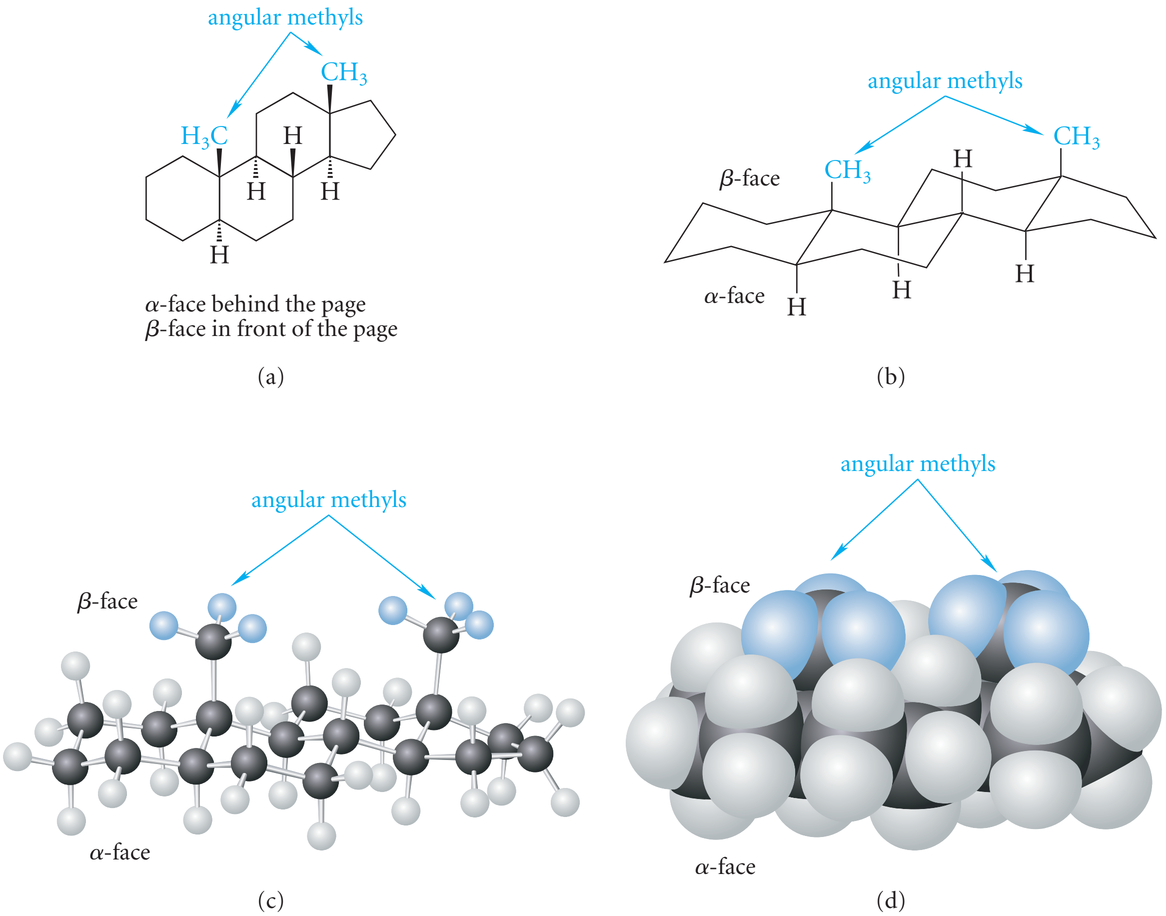
cortisone
(anti-inflammatory hormone)



progesterone
(human female sex hormone)



testosterone
(human male sex hormone)

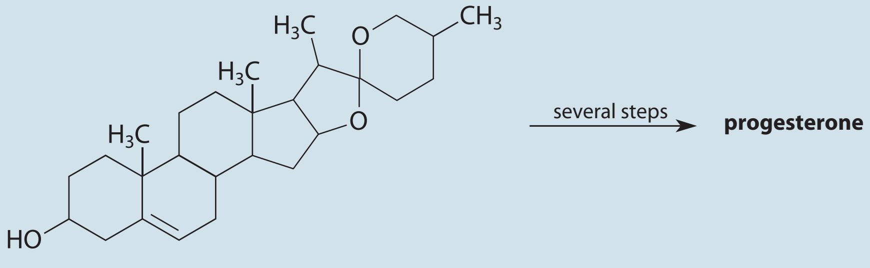


(a) (b) (c) (d)

Figure 7.13 Four different representations of the steroid ring system. (a) A planar structure. (b) A perspective structure. (c) A ball-and-stick model. (d) A space-filling model. Notice the all-trans ring junctions and the extended, relatively flat shape. The hydrogens of the angular methyl groups are shown in blue in parts (c) and (d).

Sources of Steroids

Prior to 1940, steroids were obtained only from such inconvenient sources as sows' ovaries or the urine of pregnant mares, and they were scarce and expensive. In the 1940s, however, a Pennsylvania State University chemist, Russell Marker (1902–1995), developed a process that could bring about the conversion of a naturally occurring compound called *diosgenin* into progesterone.



diosgenin

(Various forms of this conversion, called the *Marker degradation,* are still in use.) The natural source of diosgenin is the root of a vine, *cabeza de negro,* genus *Dioscorea, which is* indigenous to Mexico. The Mexican government nationalized the collection of *Dioscorea* in the early 1970s, and subsequent overharvesting led to a decrease in the diosgenin content and a 10-fold price increase.

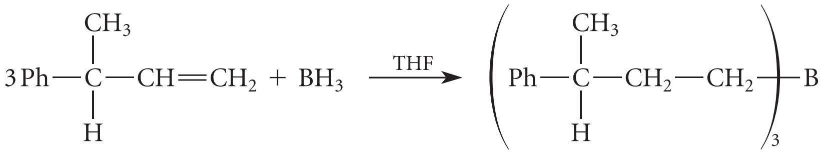
About two-thirds of modern synthetic steroid production starts with *Dioscorea,* which is now grown not only in Mexico but also in Central America, India, and China. More recently, practical industrial processes have been developed that start with steroid derivatives from other sources. For example, in the United States, a process was developed to recover steroid derivatives from the byproducts of soybean-oil production, and these are used to produce synthetic glucocorticoids and other steroid hormones. Some estrogens and cardiac steroids are still isolated directly from natural sources.

7.7 RELATIVE REACTIVITIES OF STEREOISOMERS

The remainder of this chapter focuses on the importance of stereochemistry in organic reactions. To begin, this section develops some general principles concerning the relative reactivities of stereoisomers.

A. Relative Reactivities of Enantiomers

Imagine subjecting a pair of enantiomers to the same reaction conditions. Will the reactivities of the enantiomers differ? As an example, consider the following reaction, in which a chiral alkene reacts with borane:



$$3\,\mathrm{Ph{-}\overset{CH_3}{\underset{H}{C}}{-}CH{=}CH_2} + \mathrm{BH_3} \xrightarrow{\mathrm{THF}} \left(\mathrm{Ph{-}\overset{CH_3}{\underset{H}{C}}{-}CH_2{-}CH_2}\right)_3\!\mathrm{B} \qquad (7.27)$$

(a chiral alkene)

Do the *R* and *S* enantiomers of this alkene have different reactivities? A general principle applies to situations like this. *Enantiomers react at the same rates with an achiral reagent*. This means that the enantiomers of the alkene in Eq. 7.27 react with borane, an achiral reagent, at exactly the same rates to give their respective products in exactly the same yield.

An analogy from common experience can help you understand why this should be so. Consider your feet, an enantiomeric pair of objects. Imagine placing first your right foot, then your left, in a perfectly rectangular box—an achiral object. Each foot will fit this box in exactly the same way. If the box pinches the big toe on your right foot, it will also pinch the big toe on your left foot in the same way. Just as your feet interact in the same way with the achiral box, so enantiomeric molecules react in exactly the same way with achiral reagents. Because borane is an achiral reagent, the two alkene enantiomers in Eq. 7.27 react with borane in exactly the same way.

Enantiomers have identical reactivities with achiral reagents because *enantiomers have identical free energies.* That is, free energies, like boiling points and melting points, are among the properties that do not differ between enantiomers (Sec. 6.3). Both the starting materials in Eq. 7.27 and their respective transition states are enantiomeric. The enantiomeric transition states have identical free energies, as do the enantiomeric starting materials. Because relative reactivity is determined by the difference in free energies of the transition state and starting