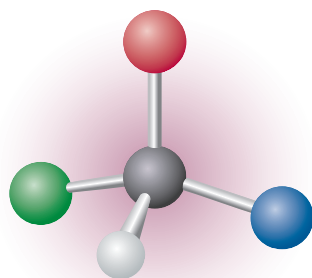


6



Principles of Stereochemistry

This chapter and the one that follows deal with stereoisomers and their properties. **Stereoisomers** are compounds that have the same atomic connectivity but a different arrangement of atoms in space. Recall that *E* and *Z* isomers of an alkene (Sec. 4.1B) are stereoisomers. In this chapter we'll learn about other types of stereoisomers.

The study of stereoisomers and the chemical effects of stereoisomerism is called **stereochemistry**. A few ideas of stereochemistry were introduced in Sec. 4.1B. This chapter delves more generally into stereochemistry by concentrating on the basic definitions and principles. We'll see how stereochemistry played a key role in the determination of the geometry of tetravalent carbon. Chapter 7 continues the discussion of stereochemistry by considering both the stereochemical aspects of cyclic compounds and the application of stereochemical principles to chemical reactions.

The use of molecular models during the study of this chapter is essential. Models will help you develop the ability to visualize three-dimensional structures and will make the two-dimensional pictures on the page “come to life.” If you use models now, your reliance on them will gradually decrease.

6.1 ENANTIOMERS, CHIRALITY, AND SYMMETRY

A. Enantiomers and Chirality

Any molecule—indeed, any object—has a mirror image. Some molecules are **congruent** to their mirror images. This means that all atoms and bonds in a molecule can be simultaneously superimposed with identical atoms and bonds in its mirror image. An example of such a molecule is ethanol, or ethyl alcohol, $\text{H}_3\text{C}-\text{CH}_2-\text{OH}$ (Fig. 6.1). Construct a model of ethanol and another model of its mirror image, and use the following procedure to show that these two models are congruent. For simplicity, use a single colored ball to represent the methyl group and a single ball of another color to represent the hydroxy ($-\text{OH}$) group. Place the two central carbons side by side and align the methyl and hydroxy groups, as shown in Fig. 6.1.

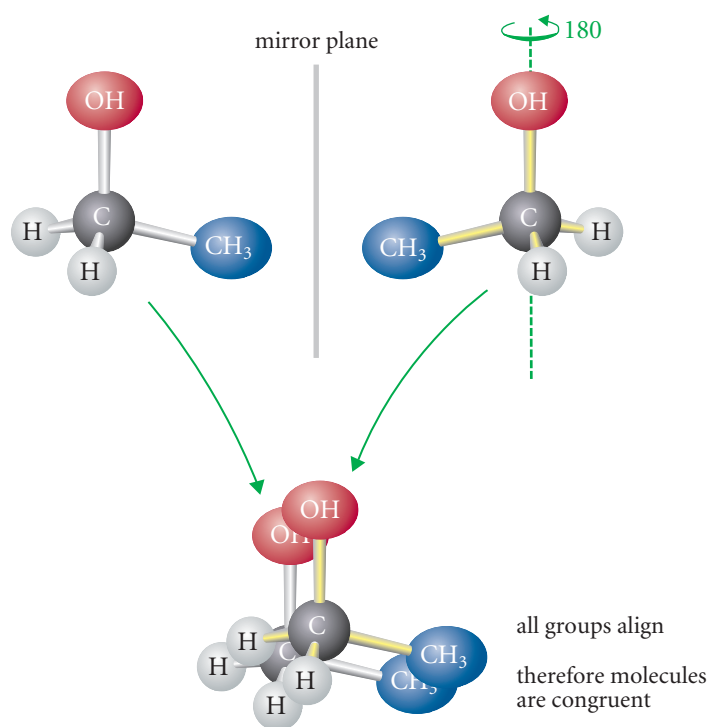
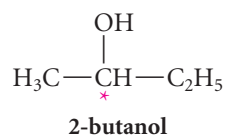


Figure 6.1 Testing mirror-image ethanol molecules for congruence. One mirror image is shown with yellow bonds to distinguish it from the other. Aligning the central carbons, the CH_3 groups, and the OH groups on the different molecules causes the hydrogens to align as well. Notice that this alignment requires rotating one of the molecules in space.

The hydrogens should then align as well. *The congruence of an ethanol molecule and its mirror image shows that they are identical.*

Some molecules, such as 2-butanol, are *not* congruent to their mirror images (Fig. 6.2, p. 228).



Build a model of 2-butanol and a second model of its mirror image. If you align the carbon with the asterisk and any two of its attached groups, the other two groups do not align. Hence, *a 2-butanol molecule and its mirror image are noncongruent and are therefore different molecules.* Because these two molecules have identical connectivities, then by definition they are *stereoisomers*. Molecules that are noncongruent mirror images are called **enantiomers**. Thus, the two 2-butanol stereoisomers are enantiomers.

Enantiomers must not only be mirror images; they must also be *noncongruent* mirror images. Thus, ethanol (Fig. 6.1) has no enantiomer because an ethanol molecule and its mirror image are congruent.

Molecules (or other objects) that can exist as enantiomers are said to be **chiral** (pronounced kī' rūl); they possess the property of **chirality**, or handedness. (*Chiral* comes from the Greek word for hand.) Enantiomeric molecules have the same relationship as the right and left

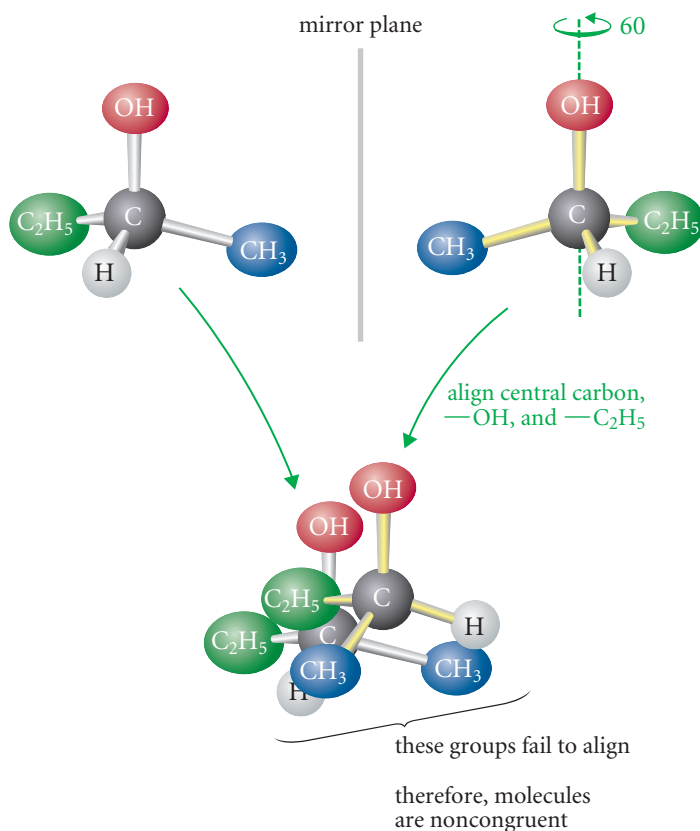


Figure 6.2 Testing mirror-image 2-butanol molecules for congruence. As in Fig. 6.1, the bonds of one mirror image are yellow. When the central carbon and any two of the groups attached to it (OH and C_2H_5 in this figure) are aligned, the remaining groups do *not* align.

hands—the relationship of an object and its noncongruent mirror image. Thus, 2-butanol is a chiral molecule. Molecules (or other objects) that are not chiral are said to be **achiral**—without chirality. Ethanol is an achiral molecule. Both chiral and achiral objects are matters of everyday acquaintance. A foot or a hand is chiral; the helical thread of a screw gives it chirality. Achiral objects include a ball and a soda straw.

Importance of Chirality

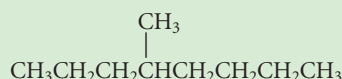
Chiral molecules occur widely throughout all of nature. For example, glucose, an important sugar and energy source, is chiral; the enantiomer of naturally occurring glucose cannot be utilized as a food source. All sugars, proteins, and nucleic acids are chiral and occur naturally in only one enantiomeric form. Chirality is important in medicine as well. Over half of the organic compounds used as drugs are chiral, and in most cases only one enantiomer has the desired physiological activity. In rare cases, the inactive enantiomer is toxic (see the story of the drug thalidomide in Sec. 6.4). The safety and effectiveness of synthetically prepared chiral drug molecules have become issues of increasing concern for both pharmaceutical manufacturers and the U.S. Food and Drug Administration (FDA).

B. Asymmetric Carbon and Stereocenters

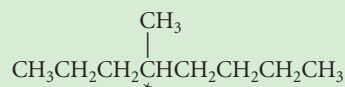
Many chiral molecules contain one or more asymmetric carbon atoms. An **asymmetric carbon atom** is a carbon to which *four different groups* are bound. Thus, 2-butanol (see Fig. 6.2), a chiral molecule, contains an asymmetric carbon atom; this is the carbon that bears the four different groups —CH_3 , $\text{—C}_2\text{H}_5$, —H , and —OH . In contrast, none of the carbons of ethanol, an achiral molecule, is asymmetric. *A molecule that contains only one asymmetric carbon is chiral.* No generalization can be made, however, for molecules with more than one asymmetric carbon. Although many molecules with two or more asymmetric carbons are indeed chiral, not all of them are (Sec. 6.7). Moreover, an asymmetric carbon atom (or other asymmetric atom) is not a *necessary* condition for chirality; some chiral molecules have no asymmetric carbons at all (Sec. 6.9). Despite these caveats, it is important to recognize asymmetric carbon atoms because so many chiral organic compounds contain them.

Study Problem 6.1

Identify the asymmetric carbon(s) in 4-methyloctane:



Solution The asymmetric carbon is marked with an asterisk:



This is an asymmetric carbon because it bears four different groups: H, CH_3 , $\text{CH}_3\text{CH}_2\text{CH}_2$, and $\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$. Notice that the propyl and butyl groups are *not* different at the point of attachment—both have CH_2 groups at that point, as well as at the next carbon removed. The difference is found at the ends of the groups. The point is that two groups are different even when the difference is remote from the carbon in question.



STUDY GUIDE LINK 6.1
Finding Asymmetric
Carbons in Rings

An asymmetric carbon atom is another type of *stereocenter*, or *stereogenic atom*. Recall (Sec. 4.1C) that a **stereocenter** is an atom at which the interchange of two groups gives a stereoisomer. In Fig. 6.2, for example, interchanging the methyl and ethyl groups in one enantiomer of 2-butanol gives the other enantiomer. If this point is unclear from Fig. 6.2, *use models to demonstrate this to yourself.* To do this, you need to build *two models*. First construct a model of either enantiomer, and then construct a model of its mirror image. Then show that the interchange of *any* two groups on one model gives the other model.

Not all carbon stereocenters are asymmetric carbons. Recall (Sec. 4.1C) that the carbons involved in the double bonds of *E* and *Z* isomers are also stereocenters. These carbons are not asymmetric carbons, though, because they are not connected to four different groups. In other words, the term *stereocenter* is not associated solely with chiral molecules. *All asymmetric atoms are stereocenters, but not all stereocenters are asymmetric atoms.*



STUDY GUIDE LINK 6.2
Stereocenters and
Asymmetric Atoms

C. Chirality and Symmetry

What causes chirality? *Chiral molecules lack certain types of symmetry.* The symmetry of any object (including a molecule) can be described by certain **symmetry elements**, which are lines, points, or planes that relate equivalent parts of an object. A very important symmetry element is a **plane of symmetry**, sometimes called an **internal mirror plane**. This is a plane that

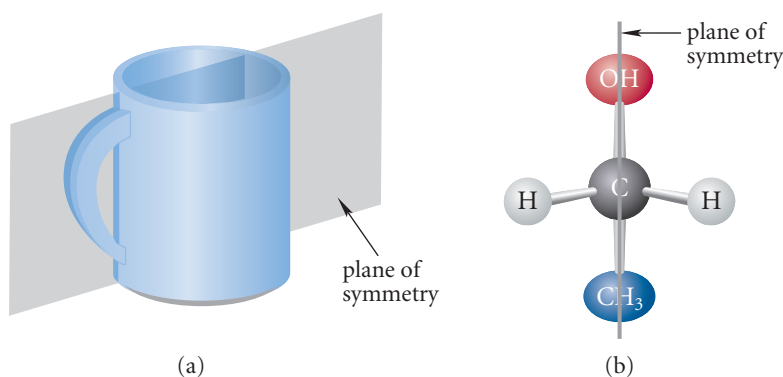


Figure 6.3 Examples of objects with a plane of symmetry. (a) A coffee mug. (b) An ethanol molecule. In the ethanol molecule, the plane bisects the H—C—H angle and cuts through the central carbon, the OH, and the CH₃.

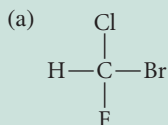
divides an object into halves that are exact mirror images. For example, the mug in Fig. 6.3a has a plane of symmetry. Similarly, the ethanol molecule shown in Fig. 6.3b also has a plane of symmetry. *A molecule or other object that has a plane of symmetry is achiral.* Thus, the ethanol molecule and the mug in Fig. 6.3 are achiral. Chiral molecules and other chiral objects do *not* have planes of symmetry. The chiral molecule 2-butanol, analyzed in Fig. 6.2, has no plane of symmetry. A human hand, also a chiral object, has no plane of symmetry.

Another important symmetry element is the **center of symmetry**, sometimes also called a *point of symmetry*. A molecule has a center of symmetry if you can reproduce it by first forming its mirror image and then rotating this mirror image by 180° about an axis perpendicular to the mirror (Fig. 6.4a). More descriptively, a center of symmetry is a point through which *any* line contacts exactly equivalent parts of the object at the same distance in both directions (Fig. 6.4b). Some objects, such as a box, can have both a center and planes of symmetry.

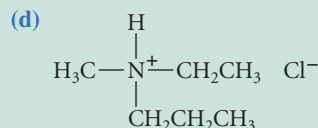
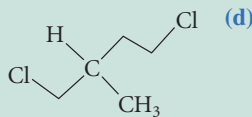
The plane of symmetry and the center of symmetry are the most common symmetry elements present in achiral objects. However, some achiral objects contain other, relatively rare, symmetry elements. How, then, can we tell whether an object is chiral? If a molecule has a single asymmetric carbon, it *must* be chiral. If a molecule has a plane of symmetry, a center of symmetry, or both, it *is not* chiral. If you are uncertain whether a molecule is chiral, *the most* general way to resolve the question is to build two models or draw two perspective structures, one of the molecule and the other of its mirror image, and then test the two for congruence. If the two mirror images are congruent, the molecule is achiral; if not, the molecule is chiral.

PROBLEMS

6.1 State whether each of the following molecules is achiral or chiral.



(b) methane (c)



6.2 Ignoring specific markings, indicate whether the following objects are chiral or achiral. (State any assumptions that you make.)

- (a) a shoe (b) a book (c) a pencil (d) a man or woman
(e) a pair of shoes (consider the pair as one object) (f) a pair of scissors

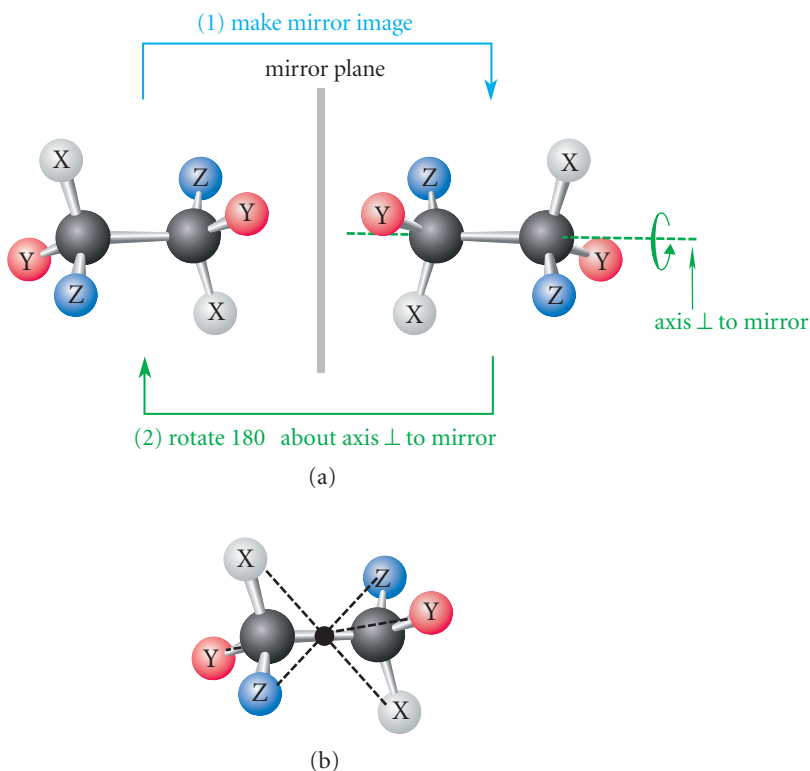
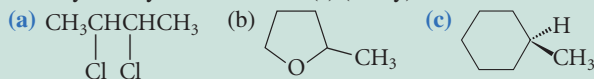


Figure 6.4 Center of symmetry. (a) If a molecule has a center of symmetry, forming the mirror image (1, *top arrow*) and then rotating the entire molecule 180° about an axis perpendicular to the mirror (2, *bottom arrow*) reproduces the molecule. (b) Any line through the center of symmetry (*black dot*) contacts equivalent points on the molecule at equal distances from the center.

6.3 Show the planes and centers of symmetry (if any) in each of the following achiral objects.

- (a) the methane molecule (b) a cone
 (c) the ethylene molecule (d) the *trans*-2-butene molecule
 (e) the *cis*-2-butene molecule (f) the staggered conformation of ethane
 (g) the anti conformation of butane

6.4 Identify the asymmetric carbon(s) (if any) in each of the following molecules.



6.2

NOMENCLATURE OF ENANTIOMERS: THE *R,S* SYSTEM

The existence of enantiomers poses a special problem in nomenclature. How do we indicate in the name of 2-butanol, for example, which enantiomer we have? It turns out that the same Cahn–Ingold–Prelog priority rules used to assign *E* and *Z* configurations to alkene stereoisomers (Sec. 4.2B) can be applied to enantiomers. (The Cahn–Ingold–Prelog rules were, in fact,