Cyclobutane

MODEL BUILDING PROBLEM 6.4

Build a model of cyclobutane. Examine the various types of strain present in the planar and nonplanar geometries.

The angles of a regular pentagon are 108°. Therefore, planar cyclopentane would have little or no angle strain. However, like planar cyclobutane, it would have considerable torsional strain because each C—C bond would be held in an eclipsed conformation. It is to be expected, then, that cyclopentane will distort from planarity to relieve this torsional strain. In one low-energy conformation, one carbon folds out of the plane so that the overall shape is somewhat like an envelope (Figure 6.10). This relieves most of the torsional strain without increasing the angle strain significantly. Overall, cyclopentane has very little strain, 6.5 kcal/mol (27 kJ/mol). It is a very common ring system and is widely distributed among naturally occurring compounds.

MODEL BUILDING PROBLEM 6.5

Build a model of cyclopentane. Examine the various types of strain present in the planar and nonplanar geometries.

6.5   CONFORMATIONS OF CYCLOHEXANE

The cyclohexane ring is very important because it is virtually strain free. This is one of the reasons why compounds containing six-membered rings are very common. If cyclohexane were planar, its C—C—C angles would be 120°—too large for the 109.5° angle of sp^3 hybrid AOs. However, the angles of the ring decrease as it becomes nonplanar. There are two nonplanar conformations, called the **chair conformation** and the **boat conformation,** that are completely free of angle strain. These conformations are shown in Figures 6.11 and 6.12, respectively. The chair conformer of cyclohexane is
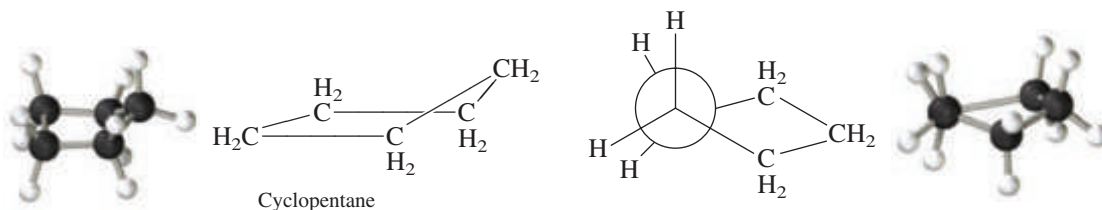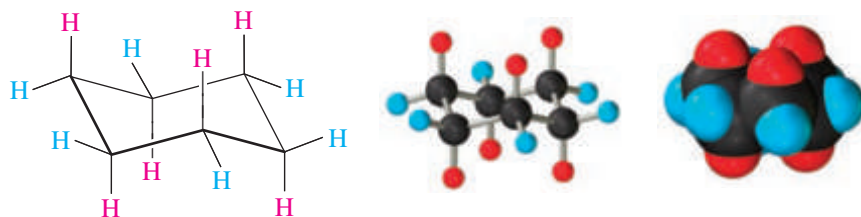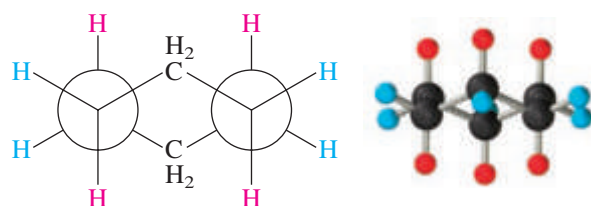

Cyclopentane

Figure 6.10

ⓐ Chair Conformation

All of the C—C—C bond angles are 109.5°, so this comformation has no angle strain. In addition, it has no torsional strain because all of the C—H bonds are perfectly staggered. This can best be seen by examining a Newman projection down C—C bonds on opposite sides of the ring:

ⓑ Newman Projection

The staggered arrangement of all the bonds can be seen clearly in the Newman projection. This same picture is seen when the projection is viewed down any C—C bond. All the C—C bonds in the molecule are in conformations in which the hydrogens are perfectly staggered.
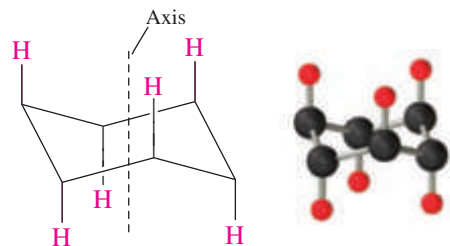
ⓒ Axial Hydrogens

In the chair conformation cyclohexane has two different types of hydrogens. The bonds to one type are parallel to the axis of the ring. These are called axial hydrogens. The axial bonds alternate up and down around the ring.

ⓓ Equatorial Hydrogens
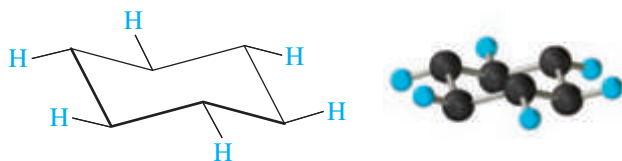
The other hydrogens are directed outward from the ring. They are called equatorial hydrogens because they lie around the "equator" of the ring. Now go back to structure ⓐ, in which both types of hydrogens are shown, and identify the axial hydrogens (red) and the equatorial hydrogens (blue). Also examine the view of the axial and equatorial hydrogens provided by the Newman projection.
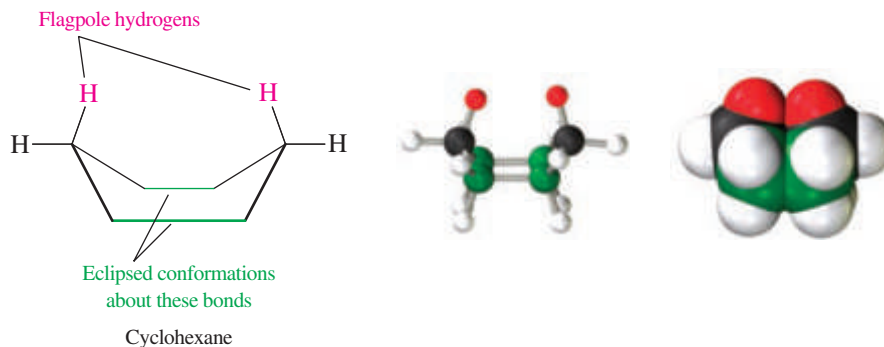
Figure 6.11

THE CHAIR CONFORMATION OF CYCLOHEXANE.
ⓐ CHAIR CONFORMATION,
ⓑ NEWMAN PROJECTION,
ⓒ AXIAL HYDROGENS, AND
ⓓ EQUATORIAL HYDROGENS.

Figure 6.12

THE BOAT CONFORMATION
OF CYCLOHEXANE. ⓐ BOAT
CONFORMATION, ⓑ NEWMAN
PROJECTION, AND ⓒ TWIST
BOAT CONFORMATION.

ⓐ **Boat conformation**

Flagpole hydrogens

Eclipsed conformations
about these bonds

Cyclohexane

Like the chair conformation, all of the C—C—C bond angles of the boat conformation are 109.5°, so it has no angle strain. However, it does have other types of strain. The two red hydrogens, called flagpole hydrogens, approach each other too closely and cause some steric strain. In addition, the conformations about the green bonds are eclipsed. This can be seen more easily in the Newman projection down these bonds:
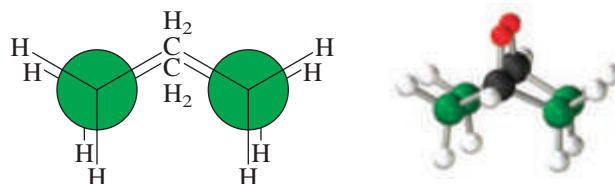
ⓑ **Newman Projection**

The Newman projection shows that two bonds of the boat conformation are eclipsed. The torsional strain due to these eclipsing interactions and the steric strain due to the interaction of the flagpole hydrogens make the boat conformation higher in energy than the chair conformation. The boat conformation is flexible enough to twist somewhat to slightly decrease its overall strain energy.

ⓒ **Twist Boat Conformation**
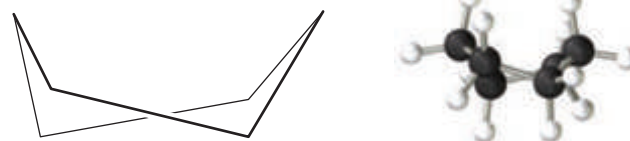
In the twist boat conformation the "bow" and the "stern" of the boat have been twisted slightly. Although this decreases the flagpole interaction and relieves some of the torsional strain, angle strain is introduced. Overall, the twist boat conformation is a little more stable than the boat conformation but not nearly as stable as the chair conformation.

perfectly staggered about all of the C—C bonds and therefore has no torsional strain either—it is strain free. The boat conformer, on the other hand, has both steric strain, due to interactions of the flagpole hydrogens, and torsional strain. It is about 6 kcal/mol (25 kJ/mol) less stable than the chair conformer. Some of the steric and torsional strain
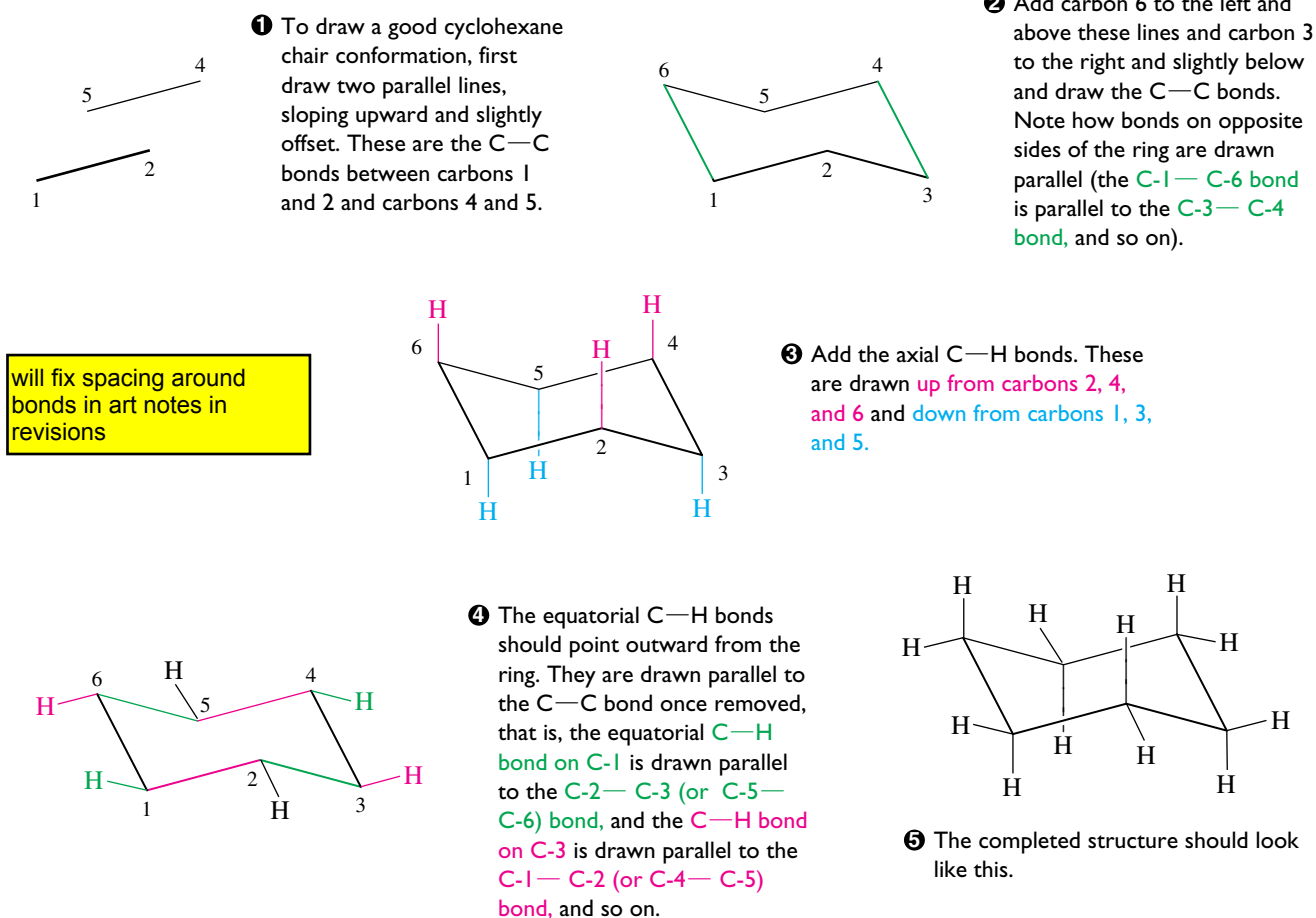
❶ To draw a good cyclohexane chair conformation, first draw two parallel lines, sloping upward and slightly offset. These are the C—C bonds between carbons 1 and 2 and carbons 4 and 5.

❷ Add carbon 6 to the left and above these lines and carbon 3 to the right and slightly below and draw the C—C bonds. Note how bonds on opposite sides of the ring are drawn parallel (the C-1— C-6 bond is parallel to the C-3— C-4 bond, and so on).

will fix spacing around bonds in art notes in revisions

❸ Add the axial C—H bonds. These are drawn up from carbons 2, 4, and 6 and down from carbons 1, 3, and 5.

❹ The equatorial C—H bonds should point outward from the ring. They are drawn parallel to the C—C bond once removed, that is, the equatorial C—H bond on C-1 is drawn parallel to the C-2— C-3 (or C-5— C-6) bond, and the C—H bond on C-3 is drawn parallel to the C-1— C-2 (or C-4— C-5) bond, and so on.

❺ The completed structure should look like this.

Figure 6.13

FIVE STEPS FOR DRAWING CHAIR CYCLOHEXANE.

of the boat can be relieved by twisting. The twist boat conformation is about 5 kcal/mol (21 kJ/mol) less stable than the chair conformation.

Figure 6.11 also shows that there are two different types of hydrogens, called **axial** hydrogens and **equatorial** hydrogens, in the chair conformer of cyclohexane. The axial C—H bonds are parallel to the axis of the ring; the equatorial C—H bonds project outward from the ring around its "equator." Steps to help you learn to draw the chair conformation of cyclohexane, including the axial and equatorial hydrogens, are provided in Figure 6.13.

The chair conformation of cyclohexane is not rigid. It can convert to a twist boat comformation and then to a new chair conformation in a process termed ring-flipping, as shown Figure 6.14 (not all the hydrogens are shown for clarity).

In the ring-flipping process, C-1 flips up to give a twist boat. Then C-4 can flip down to produce another chair conformation. When opposite carbons flip like this, all axial and equatorial bonds interconvert; that is, all hydrogens that were axial are converted to equa-
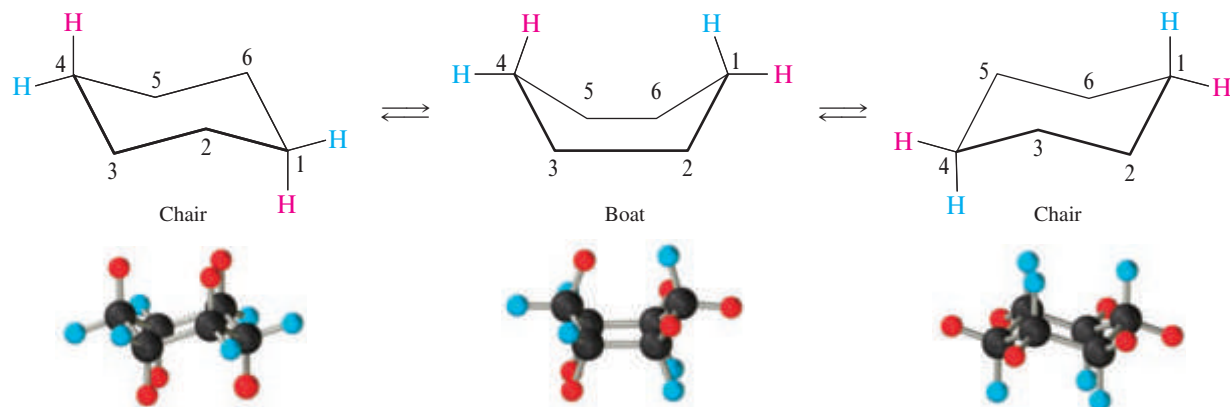
Figure 6.14

RING-FLIPPING. Converting chair cyclohexane to boat and then to a new chair.

torial, and all hydrogens that were equatorial are converted to axial. This can be seen in Figure 6.14, in which the red hydrogens, which are axial in the left chair, are converted to equatorial hydrogens in the right chair. The energy required for this ring-flipping process is shown in Figure 6.15. The highest barrier, called the half-chair conformation, is about 10.5 kcal/mol (44 kJ/mol) higher in energy than the chair conformation. Again, the 20 kcal/mol (83.7 kJ/mol) of energy that is available at room temperature provides plenty of energy to surmount this barrier; therefore, this ring-flipping is fast. It occurs about 100,000 times per second at room temperature.

Figure 6.15

ENERGY DIAGRAM FOR THE CYCLOHEXANE RING-FLIPPING PROCESS.
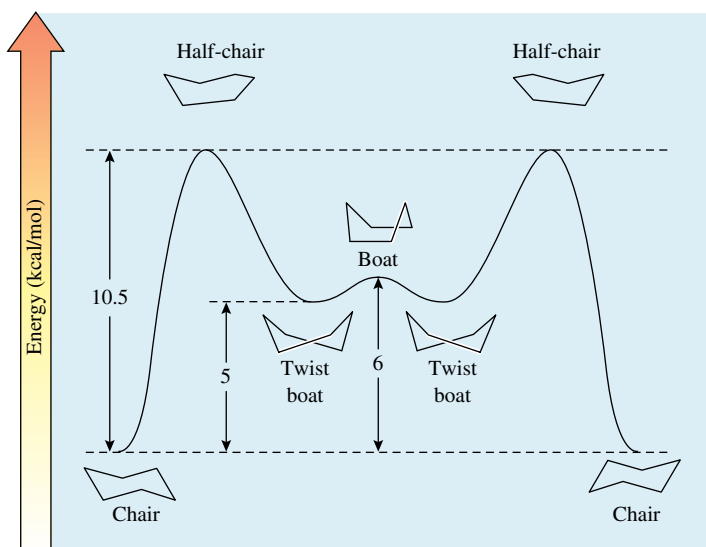
MODEL BUILDING PROBLEM 6.6
Build a model of cyclohexane.

a) Examine the strain present when the geometry is planar.
b) Examine the strain present in the boat conformation.
c) What strain is introduced in the twist boat conformation? What strain is relieved?
d) Examine the strain present in the chair conformation. Examine the conformations about one of the C±C bonds. Identify the axial and equatorial hydrogens.
e) Try a ring flip with your model. Label an axial hydrogen and determine what happens to it when the ring flips.

MODEL BUILDING PROBLEM 6.7
Draw a chair cyclohexane. Show the axial and equatorial hydrogens.
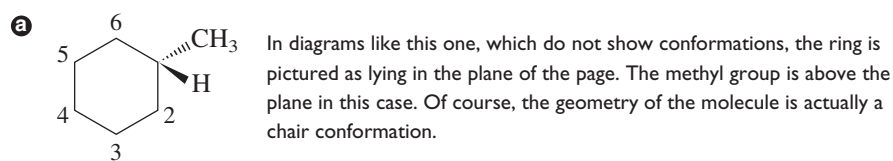
6.6 CONFORMATIONS OF OTHER RINGS

Conformational analysis of rings larger than cyclohexane is more complicated. These rings are also less common than cyclohexane, so we discuss their conformations only briefly. As can be seen from Table 6.1, the seven-membered ring compound cycloheptane has only a small amount of strain. Obviously, it is nonplanar to avoid angle strain. It does have some torsional strain, but the overall strain is comparable to that of cyclopentane. It is a fairly common ring system.

Larger rings, having from 8 to 11 carbons, have somewhat more strain than cycloheptane. They are nonplanar, but even so, they seem to have some strain due to bond angles that are too large for the tetrahedral bond angle of 109.5°. They also have some torsional strain. In addition, these rings have a new type of strain, called **transannular** or **cross-ring strain.** This occurs because some C—H bonds are forced to point toward the center of the ring. The hydrogens of these bonds experience steric crowding from their interactions with atoms on the other side of the ring. Rings of 12 or more carbons no longer have transannular strain and are essentially strain-free.
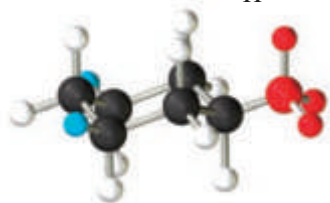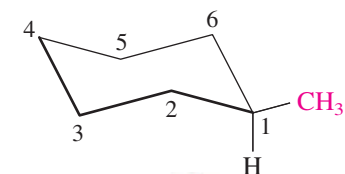
Compounds that contain a benzene ring are also quite common and important. The carbons of benzene are sp^2 hybridized, with bond angles of 120°, which match exactly the angles of a regular hexagon. Thus, benzene is a planar molecule with no angle strain. It is rigid because any deviation from planarity would increase angle strain and decrease the overlap of the p orbitals of the conjugated pi system.

Benzene
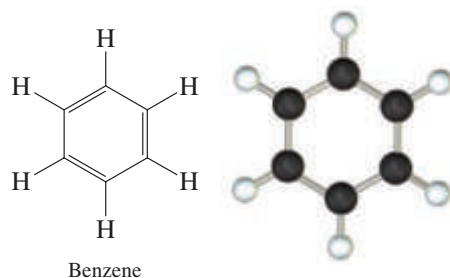
In summary, small (3- and 4-membered) rings have a large amount of strain, due primarily to angle strain with some contribution from torsional strain. Rings that have

ⓐ

6
5   CH₃
            H
4   2

3

Methylcyclohexane

In diagrams like this one, which do not show conformations, the ring is pictured as lying in the plane of the page. The methyl group is above the plane in this case. Of course, the geometry of the molecule is actually a chair conformation.

ⓑ Chair Conformations

1,3-Diaxial interactions

4
  5   6
        2   CH₃
3   1
        H

H   CH₃
    H
5   6   1
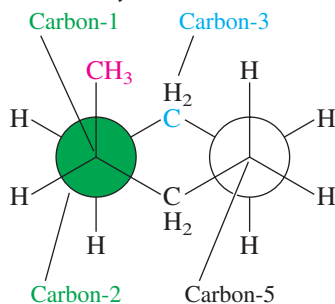   H
4   3
        2

⟷

One possible chair conformation of methylcyclohexane.

It is important to be consistent in drawing chair conformations. In this book, groups that are above the plane of the page in the flat drawing are drawn closer to the top of the page in the chair conformation. The methyl group is above the page in the flat drawing, so it is closer to the top of the page than the hydrogen. In this particular drawing, the methyl group is equatorial.
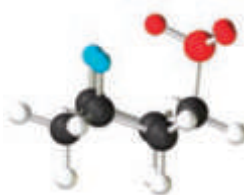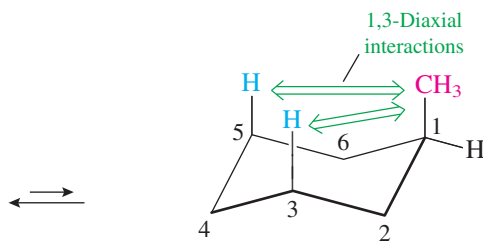
The chair produced by the ring-flipping process.

Recall that ring flips interconvert all equatorial and axial groups. Therefore, the methyl group is now axial. (But note that it is still closer to the top of the page than is the hydrogen.) The steric crowding between the axial methyl and the axial hydrogens on C-3 and C-5 destabilizes this conformer. Actually, these interactions are similar to the gauche interactions in butane. This can better be seen in the Newman projection.

ⓒ Newman Projection

Carbon-1   Carbon-3

        CH₃   H
            H₂
H   C   H

H   C   H
            H₂
        H   H

Carbon-2   Carbon-5

A Newman projection down the C-1—C-2 bond.

The methyl group on C-1 is gauche to C-3 of the ring. If a Newman projection down the C-1—C-6 bond were viewed, a similar gauche interaction between the methyl and C-5 of the ring would be found.

Figure 6.16

CONFORMATIONS OF METHYLCYCLOHEXANE. ⓐ FLAT/RING PERSPECTIVE, ⓑ CHAIR CONFORMATIONS, AND ⓒ NEWMAN PROJECTIONS.

5, 6, and 7 members have very little strain. Rings that have 8, 9, 10, and 11 members have somewhat more strain, due to a variety of interactions. Large rings (12-membered and larger) have very little strain. However, it is not just the stability of a ring that determines whether it is commonly found but also the probability of its formation. The rings that are most commonly encountered in organic compounds are those that have 3, 5, 6, and 7 members. A discussion of the reasons for this is presented in Section 8.13.

6.7   CONFORMATIONS OF CYCLOHEXANES WITH ONE SUBSTITUENT

What happens when there is a substituent on the cyclohexane ring? Let's consider methylcyclohexane as a simple example. As before, there are two chair conformations, which interconvert by the ring-flipping process. In this case, however, the two conformations are not identical. As shown in Figure 6.16, the methyl group is equatorial in one conformation and axial in the other. The conformation with the axial methyl is less stable than the conformation with the equatorial methyl by 1.7 kcal/mol (7.1 kJ/mol) because of steric interactions between the methyl and the axial hydrogens on C-3 and C-5. (These are often called **1,3-diaxial interactions.**)

Actually, in the case of a methyl substituent, each of the 1,3-diaxial interactions is identical to the interaction between the two methyl groups in the gauche conformation of butane. The last part of Figure 6.16 shows a Newman projection down the C-1—C-2 bond of the ring. The dihedral angle between the methyl group on carbon 1 and carbon 3 is 60°, just like the dihedral angle between the methyl groups in gauche butane. The axial methyl group is also gauche to C-5, as can be seen by viewing a Newman projection down the C-1—C-6 bond. Because the gauche interaction in butane destabilizes that conformation by 0.8 kcal/mol (3.3 kJ/mol), a logical estimate for the destabilization caused by the axial methyl with its two gauche interactions is twice this value, 1.6 kcal/mol (6.6 kJ/mol). This value is in reasonable agreement with the experimental value of 1.7 kcal/mol (7.1 kJ/mol) for the **axial strain energy** for a methyl group.

PROBLEM 6.7
Draw the two chair conformations for ethylcyclohexane. Which is more stable?

The two conformations of methylcyclohexane are rapidly interconverting—they are in equilibrium. The conformer with the methyl equatorial is more stable than the conformer with the methyl axial, so the equatorial conformer is present in a larger amount in the equilibrium mixture. The axial strain energy is actually the free energy difference between the conformations and can be used to calculate the equilibrium constant for the process by using the equation $\Delta G° = -RT \ln K$. Using the value of -1.7 kcal/mol (-7.1 kJ/mol) for $\Delta G°$, the equilibrium constant is calculated to be 18 at room temperature. Therefore, at any instant, 95% of methylcyclohexane molecules have the methyl group equatorial, and only 5% have the methyl axial.

PRACTICE PROBLEM 6.3

Given that the equilibrium constant for the interconversion of the axial and equatorial conformations of methylcyclohexane is 18, show how to calculate the percentage of each that is present at equilibrium.

Solution

$$\text{axial} \rightleftharpoons \text{equatorial} \quad K = \frac{[\text{equatorial}]}{[\text{axial}]} = 18$$

Let $[\text{equatorial}] = X\,\%$, then $[\text{axial}] = (100 - X)\,\%$.

$$\frac{X}{100 - X} = 18$$

$$X = 1800 - 18X$$
$$19X = 1800$$

In general, substituents larger than hydrogen prefer to be equatorial on a cyclohexane ring to avoid 1,3-diaxial interactions. Axial strain energies for a number of groups are listed in Table 6.2. Note that the values for the ethyl group (1.8 kcal/mol [7.5 kJ/mol]) and isopropyl group (2.2 kcal/mol [9.2 kJ/mol]) are only slightly larger than that for the methyl group (1.7 kcal/mol [7.1 kJ/mol]), while that for the *tert*-butyl group (4.9 kcal/mol [20.5 kJ/mol]) is much larger. The ethyl and propyl groups can be rotated so that a hydrogen is pointed back over the ring to interact with the axial hydrogens, so their effective steric bulk is not much different from that of a methyl group. In contrast, the *tert*-butyl group is forced to have one of its methyl groups pointed over the ring, causing much more severe 1,3-diaxial interactions. Because of the resulting large axial strain energy, *tert*-butylcyclohexane exists predominantly

Table 6.2   Axial Strain Energies

Group	Axial Strain Energy	Group	Axial Strain Energy
—C≡N	0.2 (0.8)	—CH$_3$	1.7 (7.1)
—F	0.25 (1.0)	—CH$_2$CH$_3$	1.8 (7.5)
—C≡CH	0.4 (1.7)	—CHCH$_3$ with CH$_3$	
—Br	0.5 (2.1)	—CHCH$_3$ (CH$_3$)	2.2 (9.2)
—Cl	0.5 (2.1)	—Ph	2.9 (12.1)
—OH	0.9 (3.8)	—CCH$_3$ with CH$_3$ above and CH$_3$ below	
—NH$_2$	1.4 (5.9)		
—COH (O double bond)	1.4 (5.9)		4.9 (20.5)

Units are kcal/mol. Values in parentheses are in units of kJ/mol.

(more than 99.9%) in the conformation with the bulky *tert*-butyl group in the equatorial position.
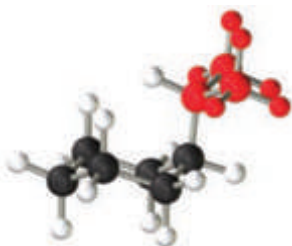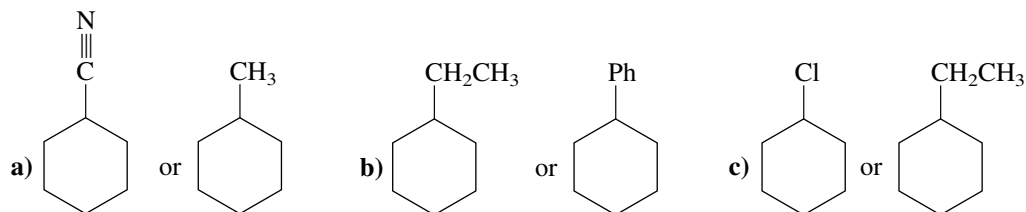
Conformation of isopropylcyclohexane
with the isopropyl group axial
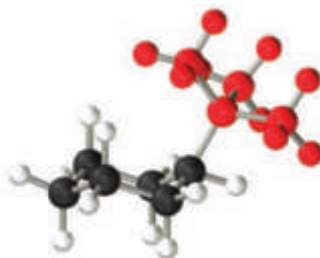
Conformation of *t*-butylcyclohexane
with the *t*-butyl group axial

PROBLEM 6.8

Which of these compounds will have more of the conformation with the substituent on the cyclohexane ring axial present at equilibrium?

a) or   **b)** or   **c)** or

PROBLEM 6.9

Bromine is larger than chlorine, yet the two atoms have identical axial destabilization energies. Explain.

6.8 CONFORMATIONS OF CYCLOHEXANES WITH TWO OR MORE SUBSTITUENTS

The presence of two or more substituents on a ring—any size ring—introduces the possibility of stereoisomers. The existence of stereoisomers is independent of conformations and should be analyzed first because different stereoisomers will have different conformations. It is easiest to examine the stereoisomers of cyclic compounds by considering the rings to be flat, even though they may actually exist in chair or other conformations. Once all the stereoisomers have been identified, the conformations of each can be scrutinized.

Let's begin by considering a simple disubstituted cyclohexane, 1,2-dimethylcyclohexane. If the ring is drawn flat, in the plane of the page, then one substituent on each carbon projects above the page and the other projects below the page. The situation is somewhat similar to the cis–trans isomerism that occurs with alkenes. Both

Focus on

How Much Strain Is Too Much?

Molecules that would have large amounts of strain energy can easily be drawn on paper, but can they be prepared—and isolated—in the laboratory? How much strain can a molecule tolerate and still exist? Questions such as these have always fascinated organic chemists and have led them to design preparations of molecules that have very large strain energies. Although some of these syntheses have not been successful, others have led to the preparation of some very interesting, and highly strained, compounds.

For example, we know that cyclobutane has considerable strain because of its four-membered ring. How many four-membered rings can be fused together in the same molecule? A fascinating test case for this question is the molecule that has eight carbon atoms arranged in a cube, known as cubane. (This is a case in which the common name, cubane, rapidly conveys the structure of the compound and, for this reason, is more useful to even experienced chemists than is the systematic name, pentacyclo[4.2.0.0^{2,5}.0^{3,8}.0^{4,7}]octane.) Cubane is also of interest because a cube is a regular polyhedron, one of Plato's perfect solids. Cubane was first prepared in 1964. Although it has considerable strain (its total strain energy has been calculated to be 166 kcal/mol [695 kJ/mol]), it is a relatively stable compound that can easily be isolated and studied. Its melting point, 130–131°C, is quite high for a molecule of this size (the melting point of octane is −57°) owing to its symmetrical shape, which allows it to pack easily into the crystal lattice.
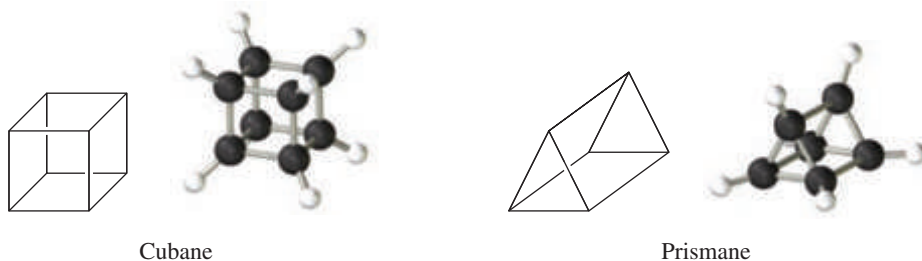
Cubane   Prismane

Prismane is an example of another interesting strained compound. Because it contains three-membered rings fused with four-membered rings, it should be even more strained than cubane. Prismane was prepared in 1973. It is a liquid that is stable at room temperature but explosive under some conditions. In toluene at 90°C its half-life (the time it takes for one-half of the compound to decompose) is 11 h. Note that prismane is isomeric with benzene. In fact, it was one of the structures proposed for benzene in the early days of organic chemistry.

The tetrahedron is another of Plato's perfect solids. The hydrocarbon having this shape is known as tetrahedrane. Because of its three-membered rings, it has considerably more strain than cubane and has, so far, resisted many attempts to prepare it. However, tetrahedrane substituted with *tert*-butyl groups at its vertices was prepared in 1981. It is a stable solid at room temperature.

Tetrahedrane   Tetra-*tert*-butyltetrahedrane
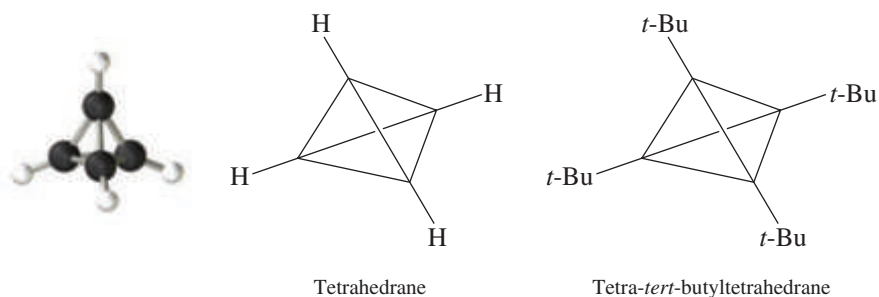
Cyclopropane has considerable strain energy. A major part of this strain energy is due to angle strain because the 60° angles of the ring are much smaller than the tetrahedral bond angle of 109.5°. Cyclopropene should have even more angle strain because the ideal angles for a double bond are 120°. Cyclopropene was first prepared in 1960. It is quite reactive and reacts with itself at room temperature. It cannot be stored for any significant period, even at temperatures as low as $-78°C$. However, 1,2-dimethyl-cyclopropene is considerably less reactive and is stable at 0°C. The methyl groups help protect the reactive double bond by hindering the approach of other reagents. Even though the cyclopropene ring has so much strain, it does occur naturally in the fatty acid malvalic acid, a component of cottonseed oil. The reactive cyclopropene ring is thought to be one of the causes of abnormalities that develop in animals that ingest cottonseed oil.


Cyclopropene   1,2-Dimethylcyclopropene

Malvalic acid
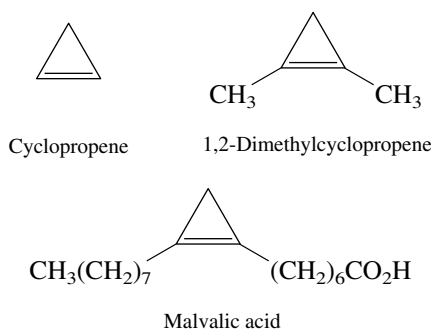
Rings of five or more carbons can accommodate a double bond without angle strain as long as that double bond is cis. However, trans double bonds are highly strained in normal-sized rings. In rings that are larger than 11 membered, the *trans*-isomer is more stable than the *cis*-isomer, as is also the case for noncyclic compounds. In rings that are 11 membered and smaller, the *cis*-isomer is more stable than the *trans*-isomer. The smallest simple *trans*-cycloalkene that has been isolated is *trans*-cyclooctene. However, even smaller examples can be generated, although their
*Continued*

lifetimes are very short. For example, *trans*-1-phenylcyclohexene has a lifetime of 9 $\times 10^{-6}$ s.

trans-Cyclooctene   Cyclooctene
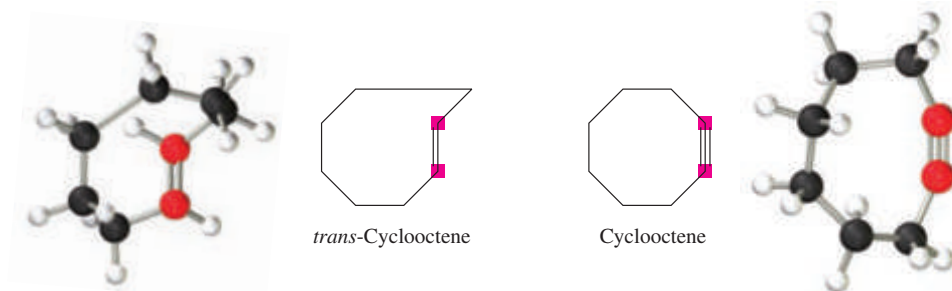
The normal bond angles for a triple bond are 180°. Incorporating four atoms (the two carbons of the triple bond and the two carbons attached to them) into a ring in a linear manner can be accomplished only in large rings. In smaller rings the triple bond will cause considerable angle strain. The smallest cycloalkyne that has been isolated is cyclooctyne, which was prepared in 1953. Again, even smaller cycloalkynes have been generated and have a transient existence. For example, 3,3,6,6-tetramethylcyclohexyne can be prepared and studied in a frozen argon matrix at 20 K, and the presence of benzyne as a transient species in a number of reactions is well accepted (see Chapter 17).

3,3,6,6-Tetramethylcyclohexane

Benzyene
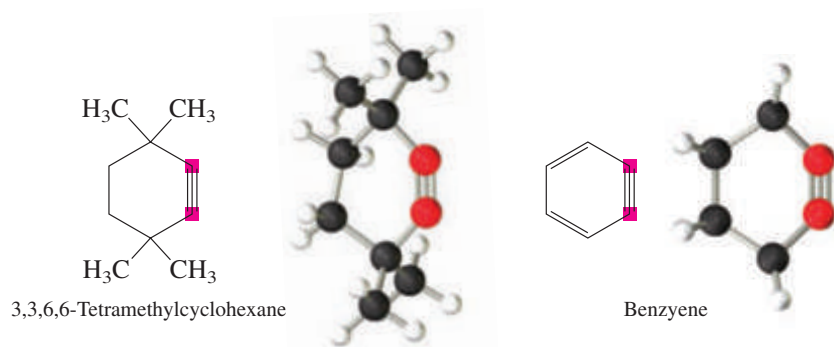
methyl groups can be above the plane of the ring (the *cis*-isomer), or one can be above and one can be below (the *trans*-isomer):

cis-1,2-Dimethylcyclohexane   *trans*-1,2-Dimethylcyclohexane
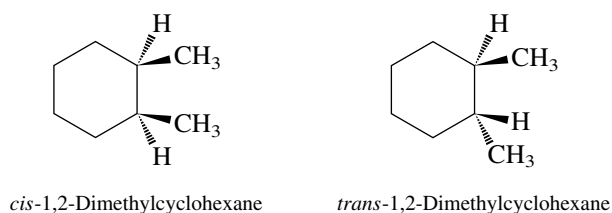
These two compounds have the same bonds but a different arrangement of these bonds in space. They are stereoisomers. Like cis–trans isomers, they cannot interconvert without breaking a bond, a process that does not occur at room temperature. Note that the same type of isomers can exist with any size ring, not just six-membered ones.

PROBLEM 6.10

Draw the stereoisomers of these compounds:

a) 1,3-Dimethylcyclohexane
b) 1,2-Diethylcyclopropane
c) 1-Chloro-3-methylcyclopentane

Let's examine the conformations of each of these stereoisomers of 1,2-dimethylcyclohexane. Those of the *cis*-isomer are shown in Figure 6.17, and those of the *trans*-isomer are shown in Figure 6.18. As can be seen in these figures, *cis*-1,2-dimethylcyclohexane exists as a mixture of two conformers, both with one axial methyl group and one equatorial methyl group and with identical strain energies of 2.5 kcal/mol (10.4 kJ/mol). The *trans*-isomer exists almost entirely in the conformation with both methyls equatorial that has a strain energy of only 0.8 kcal/mol (3.3 kJ/mol). Thus, the *trans*-isomer is more stable than the *cis*-isomer by about 1.7 kcal/mol (7.1 kJ/mol), the strain energy caused by one axial methyl group.

We must be a little cautious in generalizing these results to 1,3- and 1,4-dimethylcyclohexane. First, let's examine how the axial and equatorial positions vary as we proceed around the ring.
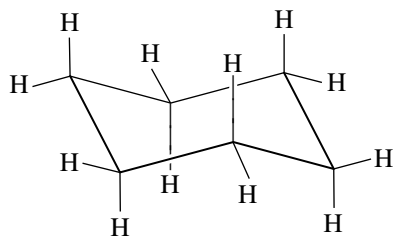

In this representation of the cyclohexane chair conformation, if the hydrogen that is closer to the top of the page is axial on one carbon, it is equatorial on the adjacent carbon. This alternation continues around the entire ring.
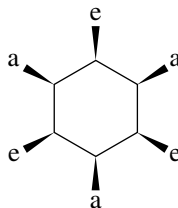
In this flat representation, then, the bonds above the plane of the page also alternate between being axial and being equatorial as one proceeds around the ring. Depending on which of the two chair conformations is examined, an "up" bond on a particular carbon may be either axial or equatorial. However, if the "up" bond at a particular carbon is axial, then the "up" bonds at both adjacent carbons are equatorial and vice versa.

On the basis of this understanding, we can now analyze the situation for the other dimethylcyclohexanes. First, consider the case of *cis*-1,3-dimethylcyclohexane. The two methyl groups will both be axial in one conformation (the less stable one), and they will both be equatorial in the other, more stable conformation. The total strain energy of the diaxial conformation cannot be calculated directly from the axial destabilization energies in Table 6.2. Recall that the strain energies listed in that table are for 1,3-diaxial interactions between the groups and the two axial hydrogens on the same side of the ring. However, the destabilization caused by a 1,3-diaxial interaction between two bulky methyl groups is considerably larger. Therefore, the diaxial conformation is expected to have a total strain energy that is larger than twice the destabilization energy due to one

ⓐ

ⓑ

ⓒ

K = 1

cis-1,2-Dimethylcyclohexane
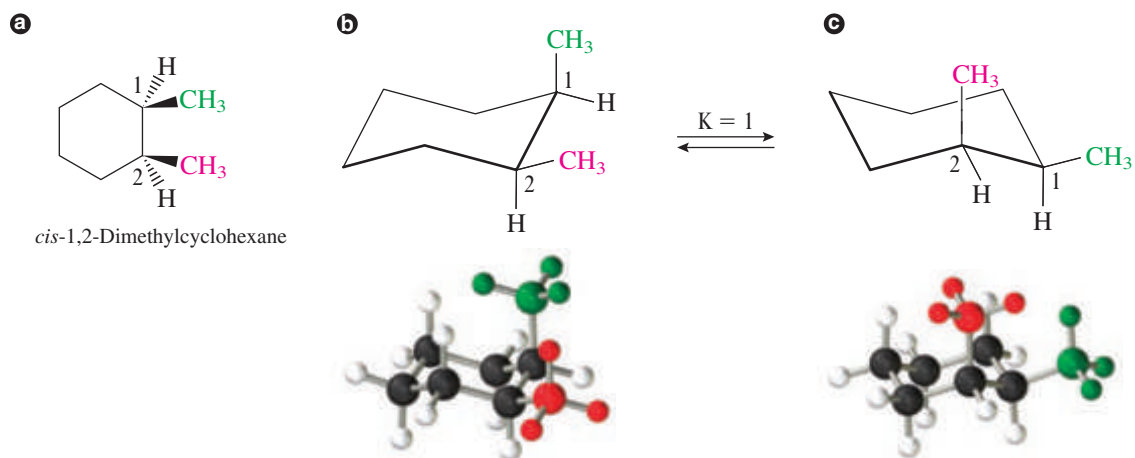
ⓐ Both methyl groups are above the plane of the page.

ⓑ Note that both methyl groups are drawn closer to the top of the page than the hydrogens, because the methyls are both above the plane of the page ⓐ. The methyl group on C-1 is axial, and the methyl group on C-2 is equatorial. The strain energy of this conformer is 1.7 kcal/mol (7.1 kJ/mol) due to the axial methyl group plus 0.8 kcal/mol (3.3 kJ/mol) due to a gauche interaction between the methyl groups, for a total of 2.5 kcal/mol (10.4 kJ/mol).

ⓒ The chair conformation produced by the ring-flipping process still has both methyl groups closer to the top of the page. The methyl group on C-1 is now equatorial, and the methyl group on C-2 is now axial. Both conformations have one axial methyl group and one equatorial methyl group, so they have identical strain energies. The equilibrium constant for the ring-flipping process is 1.0.

Figure 6.17

CONFORMATIONS OF cis-1,2-DIMETHYLCYCLOHEXANE.

axial methyl group (greater than $2 \times 1.7 = 3.4$ kcal/mol [14.2 kJ/mol]). The other conformation, with both methyl groups equatorial, has no strain energy (there is no gauche interaction between the two methyl groups because they are not on adjacent carbons) and is much more stable than the diaxial conformation. The two conformations are interconverting rapidly, but at any one instant a vast majority (more than 99.9%) of the molecules have the conformation with both methyls equatorial because this conformation is so much more stable.

For *trans*-1,3-dimethylcyclohexane, one methyl is axial and one methyl is equatorial in either conformation. Both conformations have 1.7 kcal/mol (7.1 kJ/mol) of strain energy, and the equilibrium constant for their interconversion is 1.0. The *trans*-isomer is less stable than the *cis*-isomer by 1.7 kcal/mol (7.1 kJ/mol) because of this axial methyl group.

PRACTICE PROBLEM 6.4

Draw both chair conformations of *cis*-1,3-dimethylcyclohexane. Indicate whether each methyl group is axial or equatorial.

ⓐ *trans*-1,2-Dimethylcyclohexane

$K \gg 1$
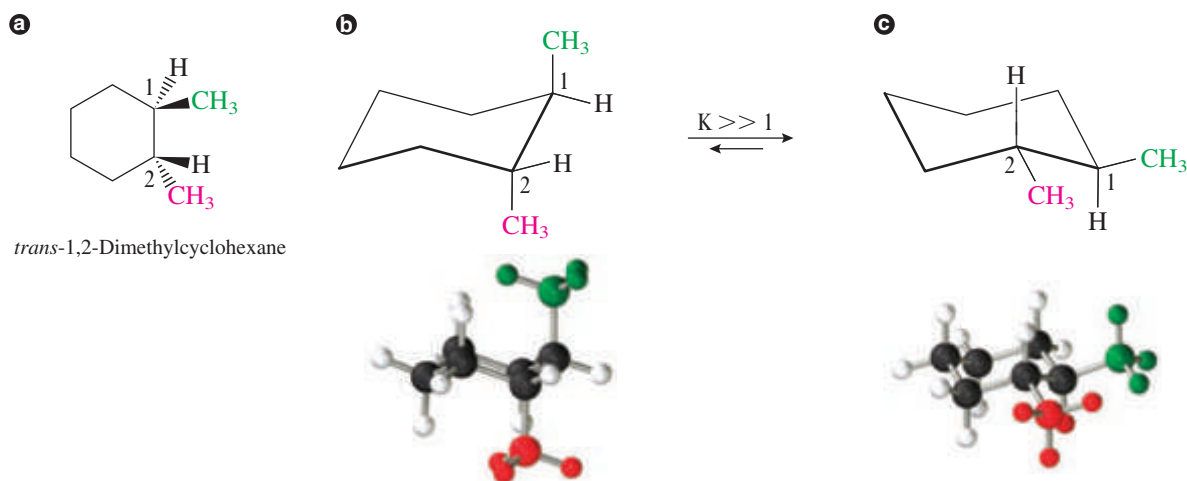
ⓐ The methyl groups are on opposite sides of the plane of the ring.

ⓑ The methyl on C-1 is closer to the top of the page, and the methyl on C-2 is closer to the bottom of the page. Both methyl groups are axial in this conformation. The strain energy due to an axial methyl is 1.7 kcal/mol (7.1 kJ/mol), so the total strain energy of this conformer is twice this value, or 3.4 kcal/mol (14.2 kJ/mol).

ⓒ The conformation produced by ring-flipping has both methyl groups equatorial and is much more stable than the other. The only strain energy present here is 0.8 kcal/mol (3.3 kJ/mol) due to a gauche interaction between the two methyl groups. Therefore, this conformer is about 2.6 kcal/mol (10.9 kJ/mol) more stable than ⓑ. The equilibrium is greatly in favor of ⓒ (>99%).

Figure 6.18

CONFORMATIONS OF *TRANS*-1,2-DIMETHYLCYCLOHEXANE.

Solution

Very large 1,3-diaxial destabilization energy

Both methyl groups are axial.

Both methyl groups are equatorial.
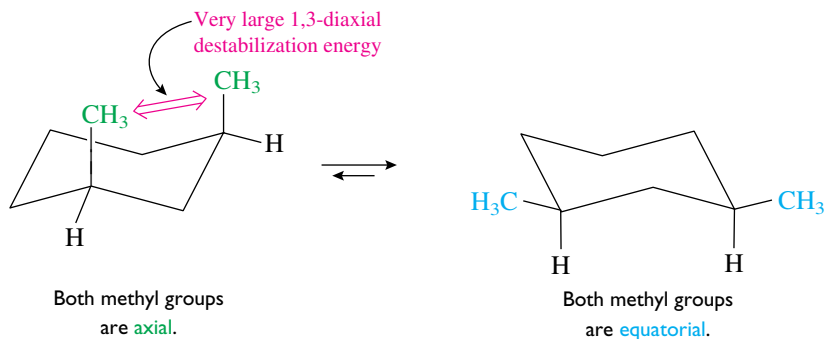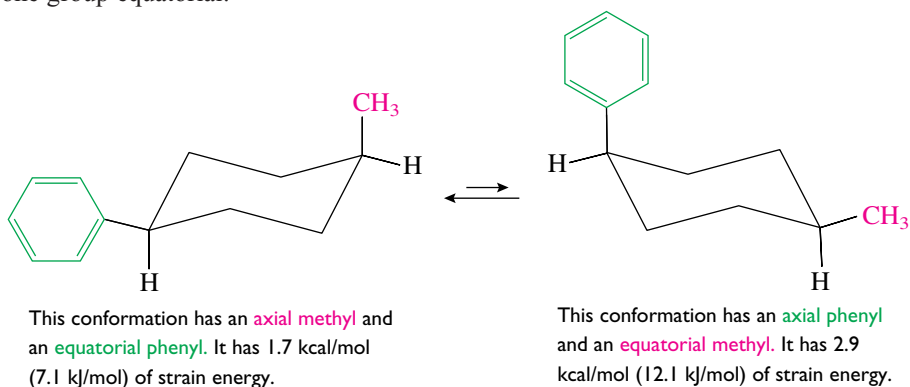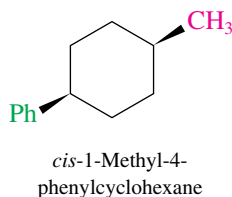
PROBLEM 6.11

Draw both chair conformations of *trans*-1,3-dimethylcyclohexane. Indicate whether each methyl group is axial or equatorial.

PROBLEM 6.12

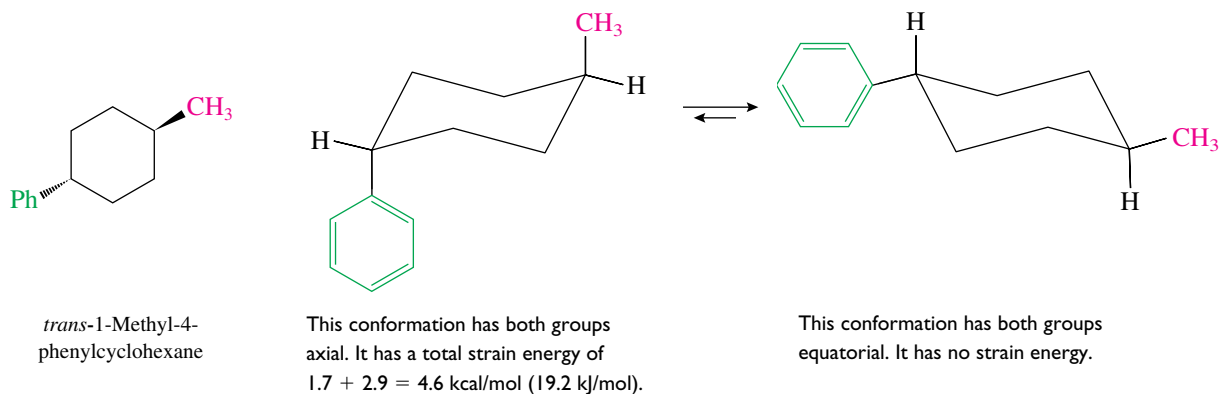Consider the two stereoisomers of 1,4-dimethylcyclohexane.

a) Explain whether each methyl is axial or equatorial in the conformations of the *cis*-isomer.

b) Explain whether each methyl is axial or equatorial in the conformations of the *trans*-isomer.

c) Explain which stereoisomer is more stable.

d) Draw the more stable conformation of the more stable stereoisomer.

What happens if there are two nonidentical groups on the ring? Let's consider the case of 1-methyl-4-phenylcyclohexane. The *cis*-isomer will have one group axial and one group equatorial:

cis-1-Methyl-4-phenylcyclohexane

This conformation has an axial methyl and an equatorial phenyl. It has 1.7 kcal/mol (7.1 kJ/mol) of strain energy.

This conformation has an axial phenyl and an equatorial methyl. It has 2.9 kcal/mol (12.1 kJ/mol) of strain energy.

The axial destabilization energy (see Table 6.2) for the phenyl group (2.9 kcal/mol [12.1 kJ/mol]) is larger than that for the methyl group (1.7 kcal/mol [7.1 kJ/mol]), so the conformation with the phenyl equatorial will be more stable by $2.9 - 1.7 = 1.2$ kcal/mol (5.0 kJ/mol), and it will predominate at equilibrium.

The conformations of *trans*-1-methyl-4-phenylcyclohexane have both groups equatorial or both groups axial:

trans-1-Methyl-4-phenylcyclohexane

This conformation has both groups axial. It has a total strain energy of $1.7 + 2.9 = 4.6$ kcal/mol (19.2 kJ/mol).

This conformation has both groups equatorial. It has no strain energy.

The conformation with both groups equatorial is obviously much more stable than the other. Overall, the *trans*-stereoisomer is more stable than the *cis*-stereoisomer by the amount of strain due to the axial methyl group in the *cis*-isomer—that is, by 1.7 kcal/mol (7.1 kJ/mol).

Determination of the relative stability of many other substituted cyclohexane stereoisomers can be done in a similar manner. However, examples in which there are complications due to 1,3-diaxial interactions between groups or examples in which the rings are substituted with polar groups, whose dipoles interact, are much more complicated. Recently, computer programs have been developed that enable the most stable conformation of many molecules, cyclic and noncyclic, to be determined. These "molecular mechanics" calculations can provide the most stable shape of even quite complex molecules.

PROBLEM 6.13

Consider the two stereoisomers of 3-isopropylcyclohexanol.
a) Which is the more stable conformation of each stereoisomer?
b) Which is the more stable stereoisomer? By how much?

PRACTICE PROBLEM 6.5

Are the substituents cis or trans in the following conformation of one of the stereoisomers of 1-ethyl-3-methylcyclohexane? Is the ethyl group axial or equatorial? Is the methyl group axial or equatorial? Which is more stable, the conformation shown or the conformation resulting from a ring-flip? Which is more stable, the compound shown or its stereoisomer?
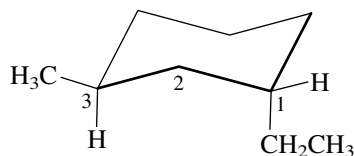

Solution

The methyl is closer to the top of the page than the H on C-3, and the H is closer to the top of the page than the ethyl on C-1, so the ethyl is trans to the methyl. Thus, this is one chair conformation of *trans*-1-ethyl-3-methylcyclohexane. In the conformation shown, the methyl is equatorial and the ethyl is axial. The ring-flipped conformation, with the methyl axial and the ethyl equatorial, is slightly more stable (by only 0.1 kcal/mol, from Table 6.2). *cis*-1-Ethyl-3-methylcyclohexane, the stereoisomer of the compound shown, is more stable because it has a conformation in which both the ethyl and the methyl groups are equatorial.

PROBLEM 6.14

For these compounds, indicate whether the substituents are cis or trans, whether they are axial or equatorial, whether the conformation shown or the other chair conforma-

tion is more stable, and whether the compound shown or one of its stereoisomers is more stable.

a)

b)

c)
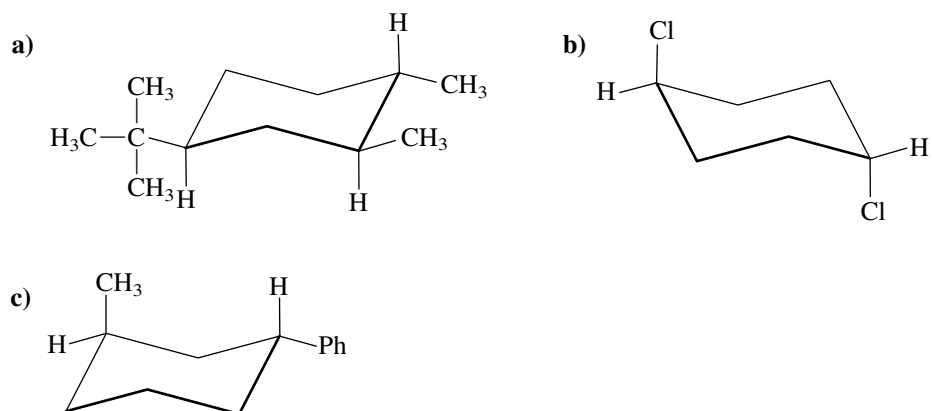
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Review of Mastery Goals

After completing this chapter, you should be able to:

■ Recognize compounds that exist as cis–trans isomers and estimate the relative stabilities of these isomers. (Problems 6.15 and 6.31)

■ Use the *Z* and *E* descriptors to designate the configurations of cis–trans isomers. (Problems 6.16, 6.17, and 6.27)

■ Determine the conformations about a C—C single bond and estimate their relative energies. (Problems 6.18, 6.19, and 6.29)

■ Determine the types and relative amounts of strain present in cyclic molecules. (Problems 6.20, 6.30, 6.32, and 6.33)

■ Draw the two chair conformations of cyclohexane derivatives and determine which is more stable. (Problems 6.21, 6.22, and 6.25)

■ Use analysis of conformations to determine the relative stabilities of stereoisomeric cyclohexane derivatives. (Problems 6.23, 6.24, and 6.26)

Additional Problems

[OrganicChemistryNow icon]
Click *Molecular Model Problems* to view the models needed to work these problems.

6.15 Draw all the cis–trans isomers for these compounds:
    a) $CH_3CH=CHCH=CHCH_2CH_3$ **b)** $CH_3CH=CHCH=CHCH_3$
    c) $CH_3CH=CHCH=CH_2$