Learning Program with Molecular Models
Conformation and Energy: Cycloalkanes

Make a model of the chair conformation of cyclohexane (see picture on p. 60 of McMurry). Note that this model requires no bending of the tetrahedral angles between the bonds attached to the carbon atoms. Three hydrogens stick up and three down relative to the carbon ring. These hydrogens (one on each carbon) are called axial. Note that the six axial hydrogens are identical (occupy identical environments); the identity of the six axial hydrogens may be more apparent if the model is turned over. The other six hydrogens (one on each carbon) are disposed around the periphery of the six-membered ring. These hydrogens are called equatorial. The six equatorial hydrogens also are identical to one another but, of course, not to the axial hydrogens.

Look at the model carefully. The conformation is called a chair because it looks like a comfortable chair from any side (i.e., it looks like this \[ \text{chair} \]). Now try to bend the model so it looks like a straight back chair (i.e., like this: \[ \text{straight} \]). Note that with this flexible model you can do this, but unless you hold on to the atoms, the model will spring back to the comfortable chair conformation (geometry). Thus, by bending the model in this way, one must be raising the energy and going to a more strained and less stable geometry. Note that if you try to keep bending in this direction (e.g. to \[ \text{twisted} \] or \[ \text{more} \]), the model becomes tremendously strained; you cannot twist the hydrogens of one carbon inside through the ring without breaking carbon-carbon bonds in your model. In practice, this is more strain than the model can tolerate. Thus, the comfortable chair (\[ \text{chair} \]) conformation may be considered a stable or low energy conformation at one rotational extreme.

Try to bend the back or leg part of your chair cyclohexane in the other direction (i.e., to this geometry: \[ \text{twisted} \]). This is a less stable (more strained) geometry. You can tell this in 3 ways. First, the amount of effort in bending increases continuously as you approach this flat geometry. Second, some of the plastic carbon-carbon bonds are no longer straight but are slightly curved or bent. Third, the carbon at the end of your model will easily flip up or down if touched (\[ \text{flipped} \]). (If it doesn’t, your bond connections are too tight and should be twisted a lot or whittled to loosen them).

Now let the end carbon flip up. You have formed a boat conformation of cyclohexane: that is, you have a conformation which looks like a boat from the side (\[ \text{boat} \]). Note there is no angle strain in the boat conformation. This is a stable (low energy) conformation. If you squeeze the two boat ends together (i.e., to \[ \text{tightly} \]), you create angle strain by the 3 criteria already outlined, and if you let go of the two ends, the molecule will spring back to the original boat. The boat conformation may thus be considered a low energy conformation at one rotational extreme. In terms of angle strain, there is no obvious difference between the chair and boat conformations (no angle strain in either form). However, chemists know from special physical measurements that the chair form is more stable.

The reason the chair is more stable is that there are fewer eclipsing interaction between atoms on adjacent carbons (less torsional strain). In fact, if you look down each carbon-carbon bond in chair cyclohexane, you will find perfect staggering between the 3 atoms (2H’s and 1C) sticking out from the front carbon with respect to the 3 atoms sticking out from the back carbon. Now look down each carbon-carbon bond of your boat model. How many eclipsing interactions do you see? In a drawing of boat cyclohexane note all the eclipsing interactions. Note also that the stability of “boat cyclohexane” is reduced further because the “flagpole” hydrogens (\[ \text{flagpole} \]) are close enough to interfere with one another. At any moment, most of the molecules in a sample of cyclohexane have the chair conformation.

The chair conformation of cyclohexane is pretty rigid – even a slight bending from this preferred geometry requires a surprisingly large amount of force. Check this. Now try to twist the boat conformation. You should find it flexible toward certain kinds of twists. For example, if you take one of the carbons forming the bottom of your boat (\[ \text{bottom} \]) and bend it toward the carbon furthest from it, this will be very easy. In the process you will form a new boat in which the carbons you have pulled together will be the front and back
points. You can go from one boat to another by grabbing the front and back top boat carbons and pulling them apart while twisting them clockwise or counterclockwise with respect to one another. Now twist the molecule so you stop halfway between the two boat structures. Draw this conformation in perspective. It is called a skew boat or twist boat conformation. Note that by our 3 criteria, there is no angle strain in this conformation. What has happened to the number of eclipsing interactions? Explain why you would expect a skew boat conformation to be more stable than a simple boat conformation but less stable than a chair conformation.

Make a model of cycloheptane. Using the kind of conformational analysis we have gone through with cyclohexane, bend and twist your cycloheptane model until you think you know which are the energetically best strain free conformations. Draw these and label all eclipsing interactions in each.

As a ring becomes larger, it becomes more flexible and conformational analysis becomes more difficult. Make a model of cyclodecane. Convince yourself that this molecule can assume a large number of conformations, although none in which the hydrogens on every carbon are exactly staggered with those on the adjoining carbons. The analysis of the preferred shapes of such large rings thus becomes very difficult.

Make models of cyclopropane, cyclobutane, and cyclopentane. Note that the bond angles in cyclopropane and cyclobutane are considerably less than the tetrahedral angle. There is considerable angle strain in these molecules. By contrast, cyclopentane can be put together readily with the tetrahedral carbons of the model set; the bond angle of a regular pentagon (108°) is close to the tetrahedral angle. In all of these models, the hydrogens on one carbon are eclipsed by those of the adjoining carbons. It is known that cyclobutane and cyclopentane actually adopt geometries that are slightly non-planar to reduce this unfavorable feature (even though this must be done at the cost of increasing the deviations from the tetrahedral angle and hence increasing the angle strain).

Make a model of cyclohexene (the normal cis isomer). Now try to make a model of cyclohexene with the double bond trans-substituted. Note that this can just barely be done with some models and that the molecule is enormously strained. It is not surprising, therefore, that trans-cyclohexene has never been made. If it were ever made, it would be tremendously reactive. The more strained a compound is, the more reactive it will be (remember cyclopropane is more reactive than cyclohexane). What is the smallest hydrocarbon ring containing a trans-substituted double bond which can be formed in a conformation exhibiting no angle strain?

Make a chair cyclohexane and replace all the axial hydrogen atoms with the red balls. Now take this model and bend it first into a boat and then into another chair by the exact manipulations diagrammed as follows (pathway X): \[ \text{Diagram of boat to chair conversion} \]. If you do this you will find that all the red balls are now in equatorial positions. Without breaking any bonds, can you twist your model in such a way as to obtain a chair conformation with some of the red balls in axial positions and others in equatorial positions? If so, show your instructor!

You could have accomplished the conversion of the chair conformation with all axial red balls to the chair conformation with all equatorial red balls by flattening the ring out completely and then bending the flat molecule into the desired conformation; i.e. the pathway diagrammed as follows (pathway Y): \[ \text{Diagram of chair to chair conversion} \]. Pathway Y will be the preferred pathway in nature if flat cyclohexane (\[ \text{Diagram of flat cyclohexane} \]) is more stable than the high energy point in the same conversion by pathway X. This latter would be \[ \text{Diagram of high energy point} \] which are obviously of equivalent energy. By appraising the amount of angle strain and the number of eclipsing interactions in \[ \text{Diagram of eclipsing interactions} \] and in \[ \text{Diagram of eclipsing interactions} \], determine whether one cyclohexane chair prefers to go to the other cyclohexane chair by pathway X or by pathway Y. Note your conclusion and your reasons.

The motions that transform a chair conformation into another chair conformation, in which all of the axial substituents have been transformed into equatorial substituents (and vice versa), generally are rapid at ordinary temperatures. Therefore, over a brief interval of time, a given substituent will be sometimes in an axial and sometimes in an equatorial position. If all of the balls (red and white represented hydrogens, this would be of little significance, since the conformations with red balls axial or equatorial would be identical. However, if
the red balls represent an atom other than hydrogen, then there is a difference. This difference can be considered better with a simpler molecule. Make a model of methylcyclohexane. By the kind of flippings that you have already performed, you will see that the methyl group can occupy either an axial or an equatorial position in a chair conformation. Examine the model with the methyl group in the axial position. Note that the large methyl group is close to two axial hydrogens on the same side. This is unfavorable because the methyl and hydrogens interfere sterically. By looking down C1-C2 of the cyclohexane ring, also note the relationship of the methyl to the attached cyclohexane methylenes. Now flip to the conformation with the methyl group in the equatorial position. The methyl group is much further from any hydrogens, and only hydrogens are in axial positions. Again, look down C1-C2 and note the more favorable relationship between the methyl and the adjacent ring methylenes. Therefore, the chair conformation with the methyl group in the equatorial position is more stable. In fact, it is found experimentally that methylcyclohexane is 5-10 times more often in the equatorial chair conformation than in the axial chair conformation. Now make a model of tert-butylcyclohexane. Note that the amount of time spent in an equatorial chair conformation will be greater for tert-butylcyclohexane than for methylcyclohexane. Explain.

The following is valuable in showing one reason why understanding the considerations above can be important. In a simple cyclohexane ring, a substituent is at times in an axial position and at times in an equatorial position (generally more often in the latter). However, in some compounds a substituent is “locked” into an axial or equatorial position. Make a model of the following compound that has “fused” cyclohexane rings. This model can be constructed by first making a chair cyclohexane ring (ring A and then forming the other ring by attaching a 4-carbon chain of atoms between the equatorial positions of the starred carbons. If you do this properly, the hydrogens on the starred carbons both will be axial as shown in the drawing. Now try to flip ring A so that its equatorial substituents will become axial. You will find this to be impossible (unless you break bonds); the chain of carbon atoms in ring B is not long enough for the carbons marked with arrows to be axial substituents on adjacent carbons of ring A. Therefore, both rings are locked into particular chair conformations. Now place a substituent (X) in an axial position as shown. Note that it will be forever locked in that axial position, since the ring flipping that would place it in an equatorial chain position is impossible. A substituent placed in an equatorial position is similarly “frozen.” Fused ring structures with such restrictions are common, (e.g., in steroids). The properties of a substituent (e.g., the rate of its reaction with a reagent, or in some instances even which of two possible reactions it undergoes) can be affected by whether it is axial or equatorial; therefore, the position in which a substituent is placed can be important.
Cyclohexanes: Conformational Analysis

**cis- and trans-Isomers in 1, 3-Disubstituted Cyclohexanes**
- Newman projection of chair form (staggered)
- Newman projection of boat form (eclipsed)
- Both cis-1,3-dimethylcyclohexane
- Both diequatorial (more stable)
- Both diaxial

**cis- and trans-Isomers in 1, 2-Disubstituted Cyclohexanes**
- Both trans-1,2-dimethylcyclohexane
- Both diequatorial (more stable)
- Both diaxial

**cis- and trans-Isomers in 1, 4-Disubstituted Cyclohexanes**
- Both trans-1,4-dimethylcyclohexane
- Both diequatorial (more stable)
- Both diaxial

-equatorial-axial (here, both chairs have same stability)
- Both cis-1,2-dimethylcyclohexane
- Both cis-1,4-dimethylcyclohexane