

4a. Alkanes. Conformational Stereoisomerism. Structural Isomerism.

4a.1 Derivatives of methane.

We can replace one of the H atoms in methane with another atom or group. These atoms or groups are called *heteroatoms*. Examples: Methyl bromide, methyl iodide, methanol, methylamine, methanethiol. Here the central C atom is not quite as perfectly tetrahedral, but for our purposes, it is close enough.

If the H atom is replaced with nothing, we have three possibilities.

- We can remove just the H nucleus and leave behind two electrons -- this gives CH_3^- , with sp^3 hybridization. It has the same structure as ammonia, just one fewer proton (and neutron) in the nucleus in the center.
- We can take away the H nucleus and both electrons. This gives us CH_3^+ . The hybridization here? We don't want to waste valuable low-energy s orbital in a hybrid orbital in which there are no electrons. Instead, the valuable s electron is divided equally among the six electrons (three bonds) remaining. Three bonds means three orbitals, one s and two p. That means the third p orbital remains unhybridized. This situation is called sp^2 hybridization. Two p orbitals occupy a plane, so in sp^2 hybridization, the three hybrid orbitals are coplanar. They point 120° apart, to the corners of a triangle. The unhybridized p orbital is perpendicular to this plane.
- What if we take away the H nucleus and *one* electron? We have a situation in which $\text{CH}_3\cdot$ (methyl radical) is between sp^2 and sp^3 hybridization. It's a shallow pyramid.

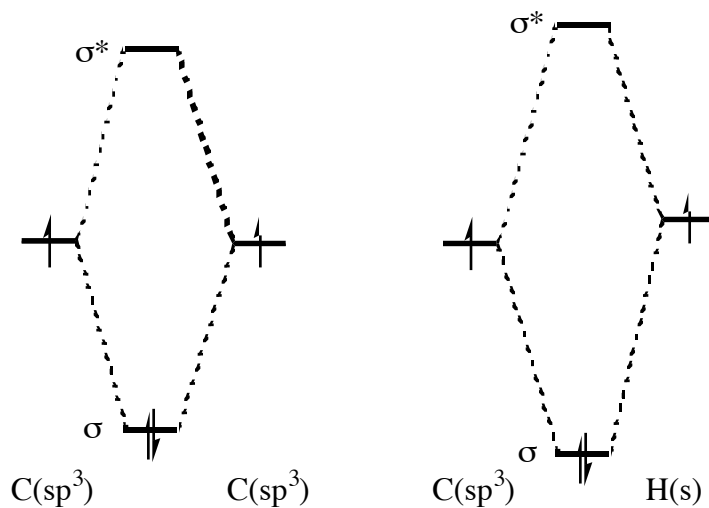
These species are high in energy and don't exist for long.

The word "methyl" also refers to a CH_3- group that is attached to the rest of a molecule. In general, the root "meth-" means "a one-carbon group". The abbreviation Me is often used for CH_3 . So MeI is the same as CH_3I .

4a.2 Ethane.

If we replace one of the H atoms in ethane with another CH_3 group, we get a compound that might be called methylmethane, but we call it *ethane*. In ethane, $\text{H}_3\text{C}-\text{CH}_3$, each C atom has four different groups attached, so each one is sp^3 -hybridized. Each C-H bond is formed by overlap of a $\text{C}(\text{sp}^3)$ orbital with a $\text{H}(\text{s})$ orbital. The C-C bond is formed by the overlap of a

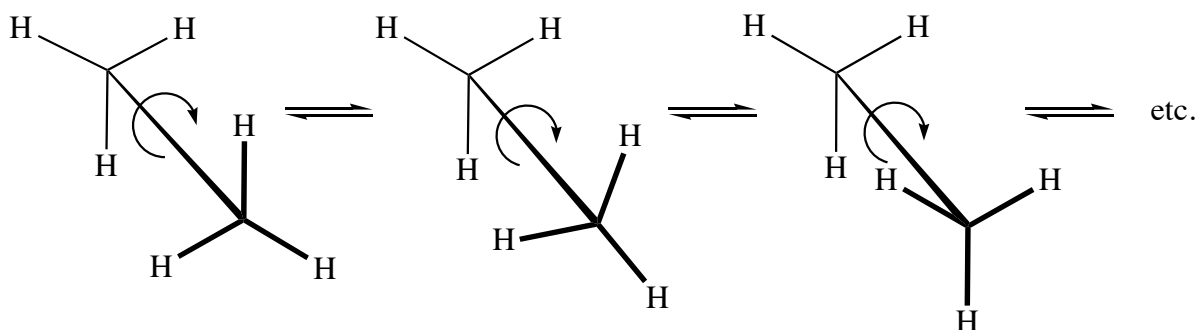
$C(sp^3)$ orbital from each atom. All of these bonds are σ bonds. A σ bond has cylindrical symmetry; if you look down the axis of the bond, it looks like a circle. As you'll see in a bit, not all bonds have that property. We can draw overlap diagrams for C–H and C–C bonds like the one we did for H–H, except, since the two constituent atomic orbitals of the C–H bond have slightly different energies, the diagram for this bond will be slightly lopsided. (A parallelepiped instead of a rhombus.) As in H_2 , anti-bonding σ^* orbitals are formed along with the bonding σ orbitals. Anti-bonding orbitals are denoted by an asterisk.



It's too much trouble to draw an orbital diagram. Instead, we tend to use just lines to indicate bonds. In the case of ethane, though, even that's a lot (seven bonds). So we use a *condensed* structure, CH_3-CH_3 , in which only the most important bond, the C–C bond, is shown.

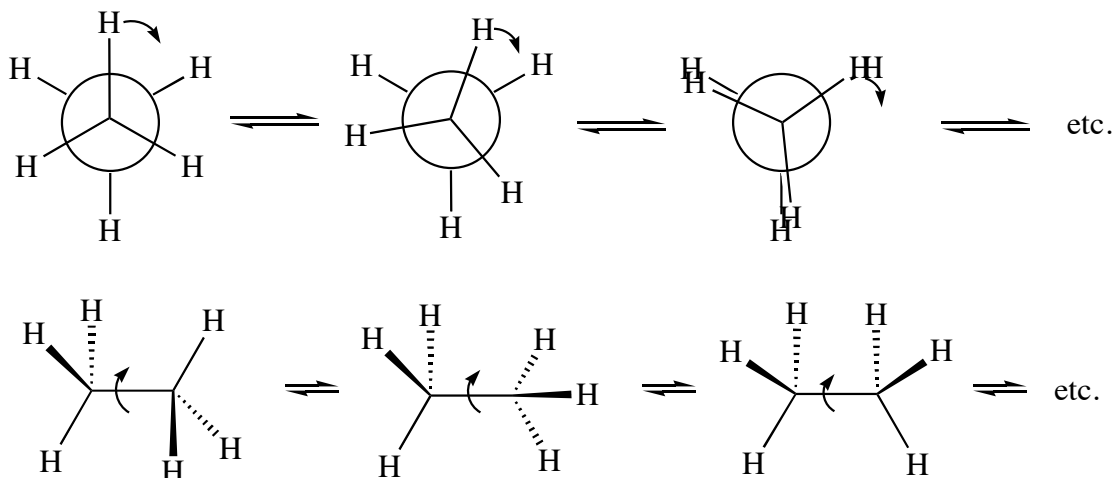
4a.3 Conformational stereoisomers of ethane.

Let's take a closer look at ethane. The C–C σ bond in ethane has cylindrical symmetry, so we can rotate the two CH_3 groups with respect to one another without changing the amount of overlap between the two sp^3 orbitals making up the σ bond. As a result, the rotation is very facile and very fast. This is most obvious if you make a model of ethane.



The three structures above have the same atoms attached to the same atoms, but the shapes of the compounds are different. As a result, they are *stereoisomers*. These particular stereoisomers can be interconverted simply by rotating about σ bonds, so they are called *conformational stereoisomers*, or *conformers* for short. Because the internal dimensions (dihedral angles, H–H distances) of the three conformers above are different, they are *conformational diastereomers*. Conformers usually interconvert so rapidly that they can't be separated from each other. This phenomenon is called *free rotation*.

There are three common ways of drawing different conformers. The *sawhorse projection* is the one that I used above. We call it “sawhorse” because that’s what it looks like. Another way of drawing conformers is called the *Newman projection*. In this projection, we look directly down the axis of the C–C σ bond, which is represented as a circle. We can see the proximal C atom, but the distal C atom is obscured by the circle of the σ bond. The bonds to the proximal C atom are fully visible, but the bonds to the distal C atom are partly obscured. The three ethane conformers drawn above are redrawn below as Newman projections. We can also use *perspective drawings* with the wedged/ hashed line formalism to indicate different conformations. These are also shown below.



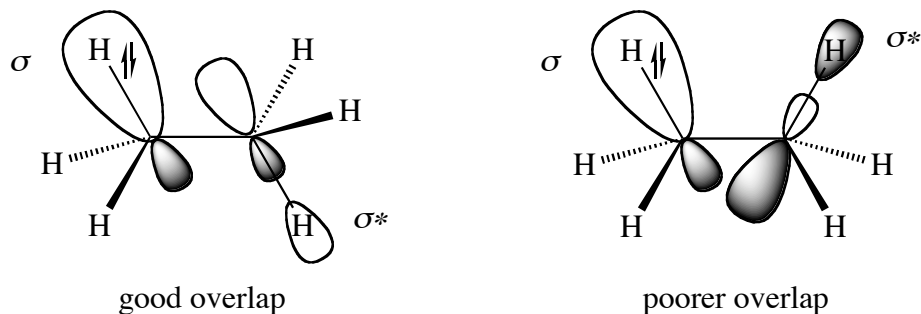
Problem for home. (1) Draw all eclipsed and staggered conformations of 1-bromo-2-chloroethane. Which of these are stereoisomeric to one another? Which are identical?

Because the different conformers of ethane are diastereomeric, we can expect that some of them are higher in energy (less stable) than others. This is in fact the case. The first and third conformers that I drew are called the *staggered* and *eclipsed* conformations of ethane. The terms refer to the mutual arrangements of the C–H bonds. The eclipsed conformer is illustrated most dramatically by the Newman projection. The eclipsed conformation is higher in energy than the staggered conformation. The actual difference in energy is 2.9 kcal/mol (12 kJ/mol), which is a small but measurable amount. (At room temperature, every 1.35 kcal/mol difference in energy means a 10-fold difference in ratio.) So rotation about the C–C σ bond is not perfectly free, but passes through an energy barrier of 2.9 kcal/mol every time it passes through the eclipsed conformation. We can draw a graph of energy versus the *dihedral angle* between two C–H bonds. (The dihedral angle of W–X–Y–Z is the angle that we see when we line X and Y up so that one is laying on top of the other, as in a Newman projection. More formally, it is the angle between the line defined by W and X and the plane defined by X, Y, and Z.)

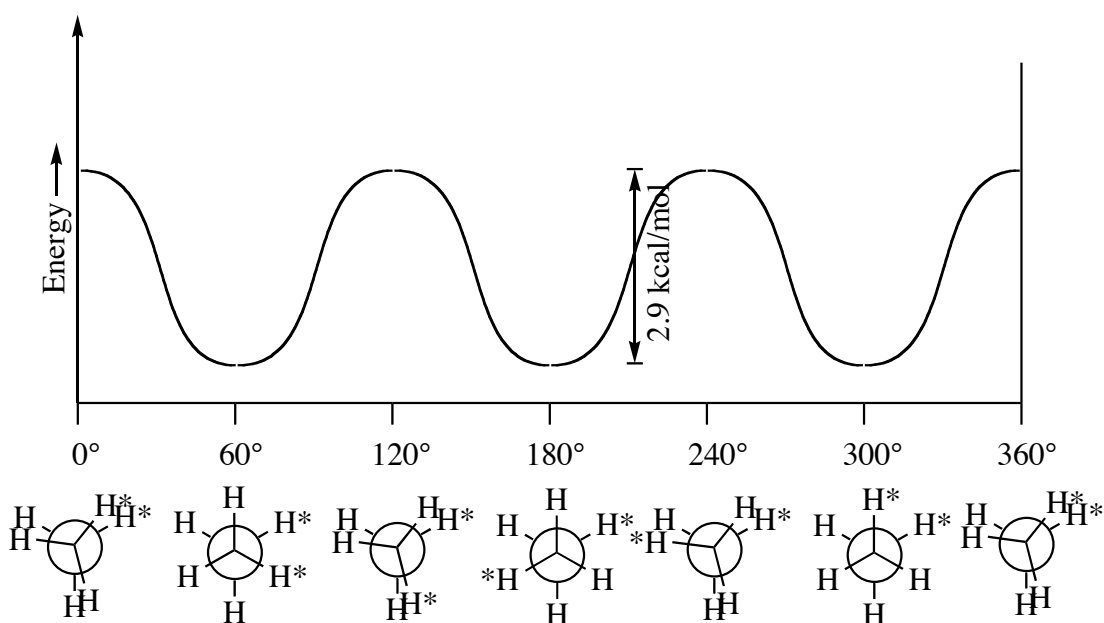
A number of points can be made regarding this graph. First of all, note that the eclipsed conformers represent energy *maxima*. A molecule in the eclipsed conformation is at unstable equilibrium, and it will not remain there for more than one molecular vibration. As a result we say that eclipsed conformers are *transition states* for the interconversion of the staggered conformers.

There are two reasons usually given for why the staggered conformer has lower energy.

1. The C–H bonds consist of electrons, and electrons repel one another, so the eclipsed conformation, where the C–H bonds are all aligned, experiences a greater amount of electronic repulsion than the staggered conformation.
2. In the staggered conformation, the orbitals of each C–H bond that contain the bonding electrons overlap better with the antibonding σ^* orbital of the staggered C–H bond. This *hyperconjugative* interaction helps to delocalize the electrons, lowering their energy. The interaction is better in the staggered conformer, because the big lobe of the σ orbital overlaps with the big lobe of the σ^* orbital. In the eclipsed conformer, the big lobe of the σ orbital overlaps with the small lobe of the σ^* orbital.



Because there are three eclipsing interactions in each eclipsed conformer, we can divide up the total energy of the eclipsed conformer, 2.9 kcal/mol, into 1.0 kcal/mol for each C–H/ C–H stabilizing interaction. The lack of stabilization in the eclipsed conformer of ethane is called *torsional strain*. We will see soon that there are other kinds of strain that can lead a particular molecule or conformer to have higher than expected energy.



4a.4 Derivatives of ethane.

We can make derivatives of ethane by replacing the H atoms in ethane. If just one of the H atoms in ethane is replaced by a different group, then the C_2H_5 group is called an *ethyl* group. So C_2H_5OH is called *ethyl alcohol*, C_2H_5Cl is called *ethyl chloride*, etc. Another way of naming these compounds is to call them derivatives of ethane. So C_2H_5Br is ethane, but with one bromine replacing a H, so we call it *bromoethane*. By this logic, we might call C_2H_5OH

hydroxyethane. However, the OH group is so important that it is given its own suffix, -ol (as in alcohol). So ethane with one H replaced by the OH group is called *ethanol*.

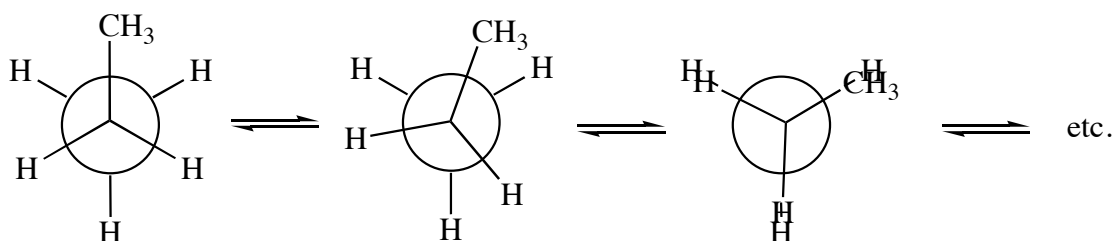
The word "ethyl" also refers to a $\text{CH}_3\text{-}$ group that is attached to the rest of a molecule. In general, the root "eth-" means "a two-carbon group" (with associated H atoms). The abbreviation Et is often used for $\text{CH}_3\text{CH}_2\text{-}$. So EtOH is the same as $\text{CH}_3\text{CH}_2\text{OH}$.

Problem for class. What is CH_3OH called?

4a.5 Propane & its derivatives. Skeletal isomerism.

Higher alkanes can be made by replacing more H atoms. Replace one of the H atoms of ethane (it doesn't matter which, they're all equivalent) with another CH_3 group. We now have a three-carbon compound, *propane*.

If we look down one of the C–C bonds of propane, we see that we can have different conformers. There is one kind of staggered conformer, and one kind of eclipsed conformer. The barrier to rotation about the C–C bonds in propane is 3.4 kcal/mol, which is higher than the barrier for ethane (2.9 kcal/mol). The reason is that C is slightly more electronegative than H (2.5 vs. 2.1 on the Pauling scale), so the C–C σ^* orbital is slightly lower in energy than the C–H σ^* orbital, so the hyperconjugative interaction between the C–H σ bond and the C–C σ^* orbital in staggered propane is slightly more favorable than that between the C–H σ bond and the C–H σ^* orbital (1.5 kcal/mol vs. 1.0 kcal/mol).



Propane has a property that is not present in ethane or methane. There are two different kinds of C atoms in propane, and there are two different kinds of H atoms. The terminal CH_3 groups in propane (which are indistinguishable, or *equivalent*) are called methyl groups, and the middle CH_2 group is called a *methylene* group. The H atoms on the CH_3 groups are called *primary* (1°), and the H atoms on the methylene group are called *secondary* (2°).

If we want to make a derivative of propane by replacing a H atom with a heteroatom, we now have two different H atoms we can choose from. If we replace a 3° H atom with X, we have a different compound from if we replace the middle H atom. Replacing a 3° H atom gives what are called *propyl* compounds or (old-fashioned) *n-propyl* compounds. Replacing a 2° H atom gives *isopropyl* compounds. So, if X = OH, we have isopropyl alcohol, or isopropanol (rubbing alcohol). The abbreviations Pr and *i*-Pr (or ⁱPr, or iPr) are often used for propyl and isopropyl.

Isopropanol and propanol have the same chemical formula, but the atom-to-atom connections are different. They are called *skeletal isomers* (a.k.a. *constitutional isomers*). Skeletal isomers have different properties — taste, smell, melting point, boiling point, everything. They are as different as if their elemental compositions were different. This concept is incredibly important. The different properties of skeletal isomers is one reason why there is such a diversity of organic compounds.

We have already met another kind of isomer. Eclipsed and staggered ethane (or propane) have the same atom-atom-atom connections, but different shapes. They are *stereoisomers*. Skeletal isomers and stereoisomers are the two different kinds of isomers. Stereoisomers can be further subdivided into four types. We have already met *conformational diastereomers*, one of those four types. We will soon meet the other three types.

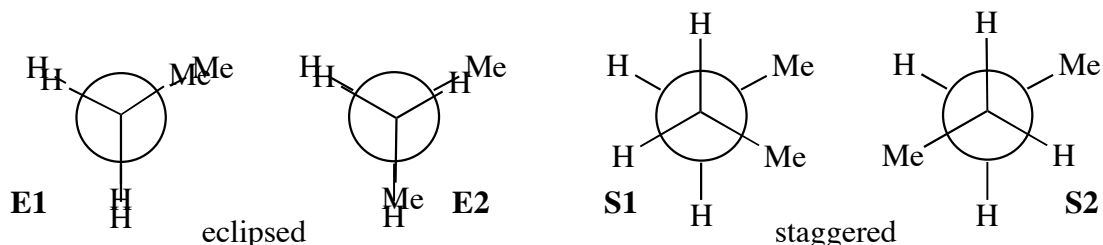
The root "prop-" means "a three-carbon group with the associated hydrogens".

4a.6 *Butane & its derivatives.*

Suppose we want to add one more carbon to propane. We have two different kinds of H we can replace, a methylene H or a methyl H. If we replace the methyl H, we have *butane*. If we replace the methylene H, we have an isomer of butane. This isomer of butane has a common or trivial name, *isobutane*. More systematically, we can think of it as propane with a methyl group on the second carbon, or 2-methylpropane (all one word).

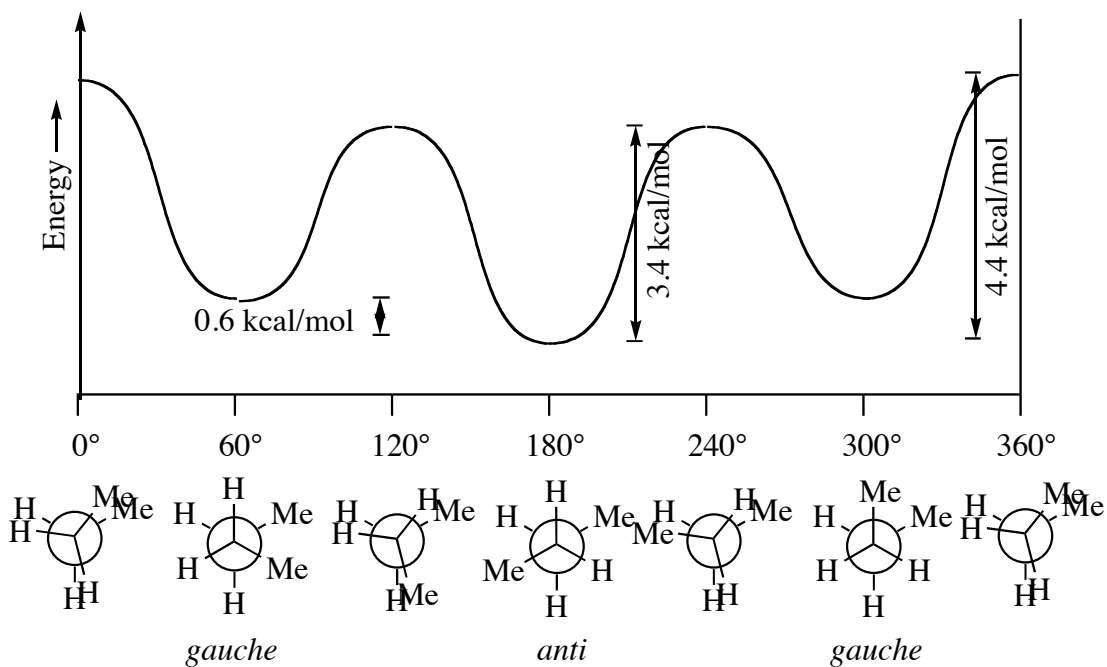
If we look down the C1–C2 σ bond, we get a picture that is identical to that of propane, except that the Me in propane is replaced by Et. The graph of energy vs. dihedral angle about the C1–C2 bond in butane doesn't look terribly different from propane. The C2–C3 bond is more interesting. We get two staggered conformational diastereomers (**S1** and **S2**) and two eclipsed conformational diastereomers (**E1** and **E2**). In **S2** the two Me groups are as far apart as possible, with a dihedral angle of 180°. It is called the *anti* conformer. In **S1**, the two Me groups are close

to one another, with a dihedral angle of 60° . It is called the *gauche* conformer. **S1** is 0.6 kcal/mol higher in energy than **S2**. (The terms “anti” and “gauche” apply only to staggered conformers.) This difference in energy is due to *steric strain*, the strain resulting from the two Me groups trying to occupy approximately the same region of space.



Among the eclipsed conformers, **E1** has two C–H/ C–H interactions and one C–Me/C–Me, and **E2** has one C–H/ C–H and two C–H/ C–Me. Neither has good hyperconjugative interactions, so the difference between them must be due to steric interactions. It turns out that the steric cost of the eclipsed C–Me/ C–Me interaction is 1.0 kcal/mol, considerably worse than the steric interaction in **S1**.

We can draw a graph of energy vs. C–C–C–C dihedral angle as follows.



Again, the eclipsed conformers are transition states, but the energy required to go through one of the eclipsed conformers is appreciably higher than the energy required to go through the other. Also, the gauche conformer is higher in energy than the anti conformer. This doesn't mean that all of the butane in any particular sample exists only in the anti conformation. There is an equilibrium between the anti and gauche conformations, and the equilibrium constant is calculated by:

$$K = e^{(-\Delta G/RT)}$$

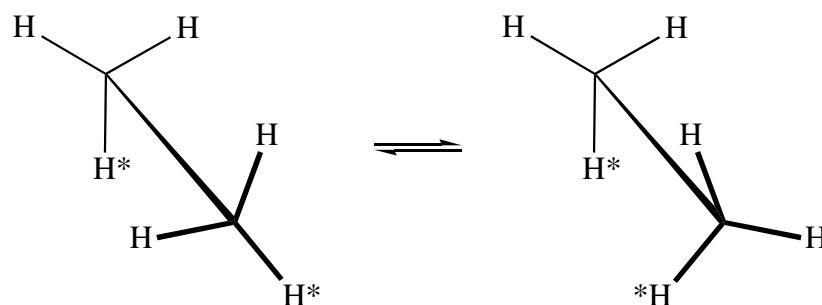
R is the universal gas constant (1.987 cal/mol·K) and T is the temperature at which the measurement is being made (usually room temperature, 295 K). Using this formula we determine that for the anti/ gauche equilibrium, $K = 4.6$ in favor of the anti conformer. So in a given sample of butane, approximately 80% of the material is in the anti conformation and approximately 20% is in the gauche conformation. (Actually, these numbers are not quite right, because we didn't consider that there are two gauche conformations and only one anti, but it gives us a ballpark estimate.)

For larger alkanes, we can conduct similar analyses. We will see that the lowest energy conformation is the one in which all C–C–C dihedral angles are 180°.

Problem. (2) Of the different conformers of 1-bromo-2-chloroethane that you drew earlier, which are anti, and which are gauche?

Let's look more closely at the two gauche conformers of butane, those with C–C–C dihedral angles of 60° and 300°. These two conformers have the same internal dimensions, e.g., the same distances between C1 and C4, the same C–C–C dihedral angle, etc. Yet the two compounds are not superimposable. One is the nonsuperimposable mirror image of the other. These two structures are *conformational enantiomers*.

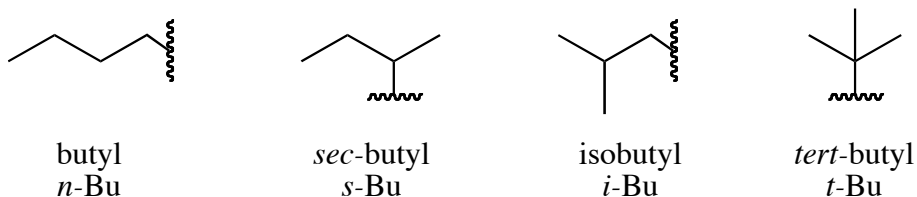
Even ethane has enantiomeric conformers. Two of these conformers are shown below. In each conformer, two H's are labeled for reference. The H*–C–C–H* dihedral angle of the conformer on the left is somewhere between 0° and 60°, say 30°. In the conformer on the right, the angle is -30°. If you make models of these two conformers, you will see that they are non-identical mirror images of one another. All the internal dimensions (atom-atom distances, dihedral angles, bond angles) are identical, but the two structures are not mutually superimposable.



Isomerism summary so far: Two structures with the same formula are isomers (or identical). If they have different atom-to-atom connections, they are *skeletal isomers*. If they have the same atom-to-atom connections, they are *stereoisomers* (or identical). Stereoisomers that can be converted into one another easily by rotating around σ bonds are *conformational stereoisomers*. (We will soon meet the other kind of stereoisomer, the *configurational stereoisomer*.) Stereoisomers that have different internal dimensions (different dihedral angles, atom-to-atom distances, etc.) are *diastereomers*. Stereoisomers that have the same internal dimensions (different dihedral angles, atom-to-atom distances, etc.), but are still not superimposable (because they are mirror images), are *enantiomers*.

You need to make models to understand these points!

Suppose we want to make a bromo derivative of butane and isobutane? In butane, we have two different kinds of H atoms, 1° and 2° , and in isobutane, we have two different kinds of H atoms, 1° and *tertiary* (3°), so we have four different kinds of bromobutanes. These are called *n*-butyl bromide, *sec*-butyl (or *s*-butyl) bromide, isobutyl bromide, and *tert*-butyl (or *t*-butyl) bromide. The more formal names are 1-bromobutane, 2-bromobutane, 1-bromo-2-methylpropane, and 2-bromo-2-methylpropane. However, the trivial names for the four butyl groups are very, very commonly used. The abbreviations *n*-Bu (or ^nBu), *i*-Bu (or ^iBu , or *i*Bu), *s*-Bu (or ^sBu), and *t*-Bu (or ^tBu) are often used for the four butyl groups. When just Bu is used, it refers to *n*-Bu.

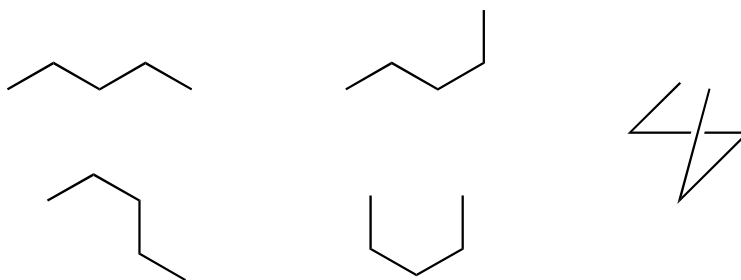


The root "but-" means "a four-carbon group with the associated hydrogens".

4a.7 Pentane & its derivatives.

From butane and isobutane we generated four different kinds of bromobutanes, so it would seem we can generate four different kinds of pentanes. However, replacing a 2° H in butane with CH₃ gives exactly the same compound as replacing a 1° H in 2-methylpropane! Both replacements give 2-methylbutane, or isopentane. Replacing a 1° H in butane gives pentane, and replacing the 3° H in 2-methylpropane gives 2,2-dimethylpropane, or neopentane.

There are many different ways to draw a compound such as pentane. The mutual orientations of the different lines can change, and the compound is still pentane. The same is true of any other compound. *What matters is the connections between the atoms, not the relative positions of the atoms!*



One more point. Methane has the formula CH₄, ethane C₂H₆, propane C₃H₈, butane and isobutane C₄H₁₀, and the three pentanes C₅H₁₂. The formula for any acyclic alkane is C_nH_{2n+2}.

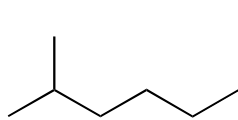
Problem for home. (3) How many bromopentanes are there?

4a.8 Higher alkanes.

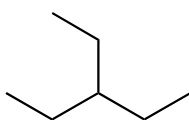
We now arrive at one of my least favorite subjects: nomenclature. We have learned about methane, ethane, propane, butane, and pentane. Above pentane, the roots of the names derive from the Greek word for that number: hexane, heptane, octane, nonane, decane, undecane, dodecane, etc. The class of compounds is called *alkanes*. The root of the alkane's name tells you how many C atoms there are; the number of H atoms in an alkane is given by the formula C_nH_{2n+2}.

A branched alkane is named as follows. Find the longest straight chain in the molecule. That provides the root of the name. Then describe the substituents on that long chain. If the

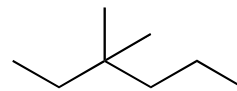
substituent has one carbon, it is methyl; if two, ethyl, etc. The position of the substituent is described by a number; if there is a choice, the number of the first substituent should be as low as possible. If there is more than one substituent of the same kind, the prefix di-, tri-, etc. is used, and the position of every group must be listed. If there is more than one substituent of different kinds, they are listed alphabetically, and the first substituent in the name should have the lowest number. You can use *i*-Pr, *s*-Bu, *i*-Bu, and *t*-Bu as substituent names.



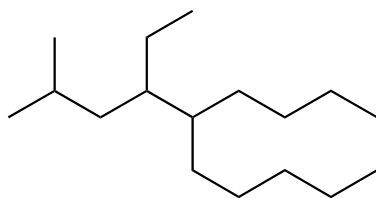
2-methylhexane



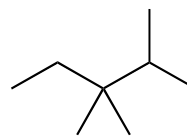
3-ethylpentane



3,3-dimethylhexane



5-butyl-4-ethyl-2-methyldecane



2,3,3-trimethylpentane

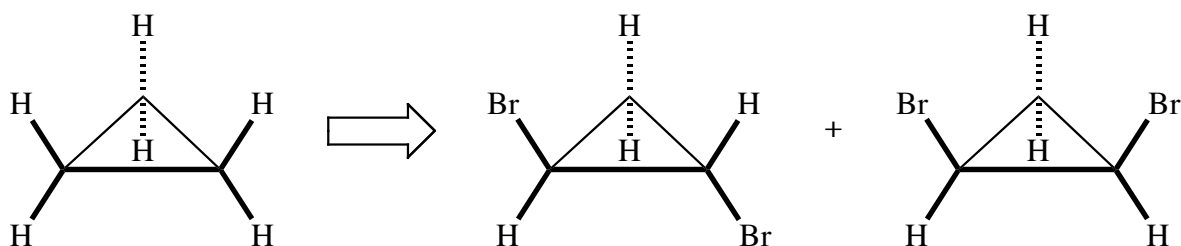
I do not expect you to name compounds. I do expect you to be able to draw a compound that I name.

4a.9 Cycloalkanes.

Let's take pentane and remove one H from each of the terminal C atoms. Then let's join the terminal two C atoms. The structure we have now has the formula C_5H_{10} . We call it *cyclopentane*. In fact, we can make cyclic alkanes of any size. A three-membered ring is cyclopropane, a four-membered ring is cyclobutane, a six-membered ring is cyclohexane, etc. The number of H atoms in a cycloalkane is given by the formula C_nH_{2n} .

When we have a cycloalkane with a single substituent, for example a fluorine atom on a six-membered ring, we call it fluorocyclohexane. No number is needed, because the ring has no beginning and no end. We can have alkyl substituents on an alkane: for example, isopropylcyclopropane. If we have more than one substituent, the alphabetically first substituent is at position 1, and the other substituent is numbered relative to the first one and as low as possible: for example, 1-fluoro-3-iodocyclooctane (not 1-fluoro-5-iodocyclooctane).

Let's look at cyclopropane from the side. The three C atoms are in a plane; three H atoms, one on each atom, point up, and three point down. Let's change one of the H atoms on one C to a Br group, and let's change another H atom on another C to a Br group. We get 1,2-dibromocyclopropane. There are two different kinds of 1,2-dibromocyclopropane that we can get, though. In one of them the two Br groups are on the same side of the ring; in the other, they are on opposite sides of the ring. These two compounds have different *shapes*. The only way to convert one of them into the other is to break a bond. Because they have different shapes, they have different properties. For example, the one with the two Br atoms on the same side of the ring has a much larger dipole moment than the other. The one with the two Br atoms on opposite sides is much thicker than the other.



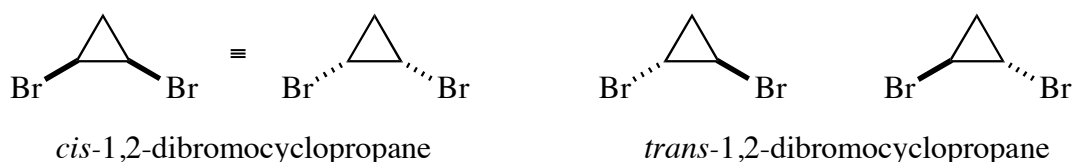
Here again we have stereoisomers, because the atom-to-atom connections are the same, but the structures are not identical. In this particular case, the internal dimensions of the compounds are different (look at the Br–Br distance and the Br–C–C–Br dihedral angle), so the compounds are *diastereomers*. However, these compounds are not conformational diastereomers, because they can't be interconverted by rotations without breaking covalent bonds. As a result, they are called *configurational diastereomers* (our third kind of stereoisomer).

Configurational diastereomers have different melting and boiling points, different reactivities, different spectral behavior ...; in short, they are completely different chemical entities. If you could separate conformational diastereomers, the same would be true of them; however, conformational diastereomers usually interconvert so rapidly on the time scale in which we operate that we can't separate them and examine their properties. As a result, we don't usually think of conformational diastereomers as being different compounds. In fact, if someone uses the word "diastereomer" without specifying conformational or configurational, you should assume that they mean configurational diastereomer. (See my online stereochemical glossary.)

Two groups that reside on the same side of a ring are called *cis*. Two groups that reside on opposite faces of a ring are called *trans*. The two compounds above would be called *trans*-1,2-dibromocyclopropane and *cis*-1,2-dibromocyclopropane.

Any time you have at least two C atoms, each of which has two non-identical groups attached, in a ring of any size, you can have *cis*–*trans* isomers.

We used the hashed–wedged line convention to denote *cis*–*trans* isomers. E.g., for 1,2-dibromocyclopropane, we write the following. (Some people use dashed lines instead of hashed lines, but dashed lines can have several different meanings, so hashed lines are better.) Note that the doubly wedged and doubly hashed structures that are drawn for the *cis* isomer are *identical*; if we pick one up out of the plane of the paper, flip it over, and put it back down, we get the other. This is not true of the two *trans* structures that are drawn; these represent examples of the fourth class of stereoisomers, *configurational enantiomers*. Enantiomers are *nonsuperimposable mirror images* of one another. One pair of enantiomers that is very familiar to you is your hands. Your left hand is an enantiomer of your right hand. They feature the same shape, the same pinkie-to-thumb distance, etc., but they are non-superimposable mirror images.



Diastereomers have different internal dimensions, i.e. dihedral angles and distances between nonbonded atoms — for example, the two Br atoms in *cis*-1,2-dibromocyclopropane are closer than they are in *trans*-1,2-dibromocyclopropane — while enantiomers have *identical* internal dimensions. Enantiomers have identical energies, whereas diastereomers differ in energy. Some compounds don't have enantiomers; for example, *cis*-1,2-dibromocyclopropane is *identical* to its mirror image. We will talk about enantiomers in much greater detail soon.

You must make models to understand the concept of stereoisomerism of cycloalkanes!

Note well that if I use the term “isomers,” I could be referring to any kind of isomer: constitutional isomer, stereoisomer, diastereomer, or enantiomer.

Problem. (3) Which of the cyclic skeletal isomers of C_5H_{10} and C_6H_{12} have *cis* and *trans* isomers? Draw them using the hashed/ wedged line convention.

Many organic compounds have more than one ring. A compound can have rings that are isolated, spiro, fused, or bridged, depending on whether they share 0, 1, 2, or >2 atoms. Any alkane with m rings in it has the formula $C_nH_{2(n-m+1)}$.

