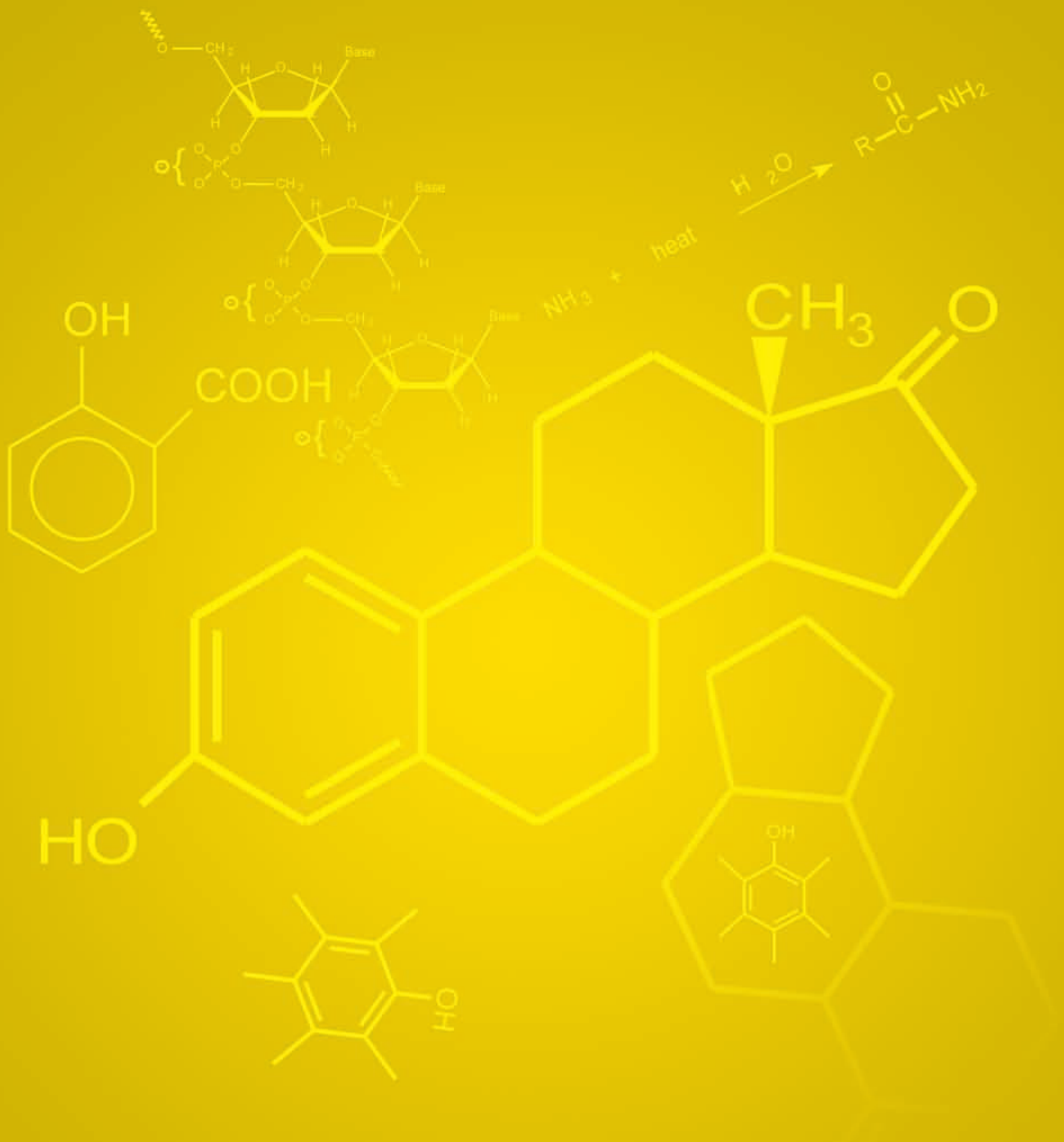

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ORGANIC CHEMISTRY

PART IV.B: BIOLOGICAL SCIENCES

IMPORTANT: Before doing your science survey for the GAMSAT, be sure you have read the Preface, Introduction and Part II, Chapter 2. The beginning of each science chapter provides guidelines as to what you should Memorize, Understand and what is Not Required. These are guides to get you a top score without getting lost in the details. Our guides have been determined from an analysis of all ACER materials plus student surveys. Additionally, the original owner of this book gets a full year access to many online features described in the Preface and Introduction including an online Forum where each chapter can be discussed.

♣ MOLECULAR STRUCTURE OF ORGANIC COMPOUNDS

Chapter 1

Memorize

- * Hybrid orbitals and geometries
- * Periodic table trends
- * Define: Lewis, dipole moments
- * Ground rules for reaction mechanisms

Understand

- * Delocalized electrons and resonance
- * Multiple bonds, length, energies
- * Basic stereochemistry
- * Principles for reaction mechanisms

Not Required *

- * Advanced level college info
- * Hybrids involving d, f, etc.

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Introduction

Organic chemistry is the study of the structure, properties, composition, reactions, and preparation (i.e. synthesis) of chemical compounds containing carbon. Such compounds may contain hydrogen, nitrogen, oxygen, the halogens as well as phosphorus, silicon and sulfur. If you master the basic rules in this chapter, you will be able to conquer GAMSAT mechanisms with little or no further memorization.

Additional Resources

Free Online Q&A + Forum

Reaction Mechanisms
Nucleophiles
Leaving Groups

Video: Online or DVD 1

Flashcards

Special guest

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* The real GAMSAT may have advanced level information presented (ie. in a passage) but previous knowledge of said information is not required to answer the questions that would follow. Practice ACER and GS practice GAMSATs can help you clarify this point.

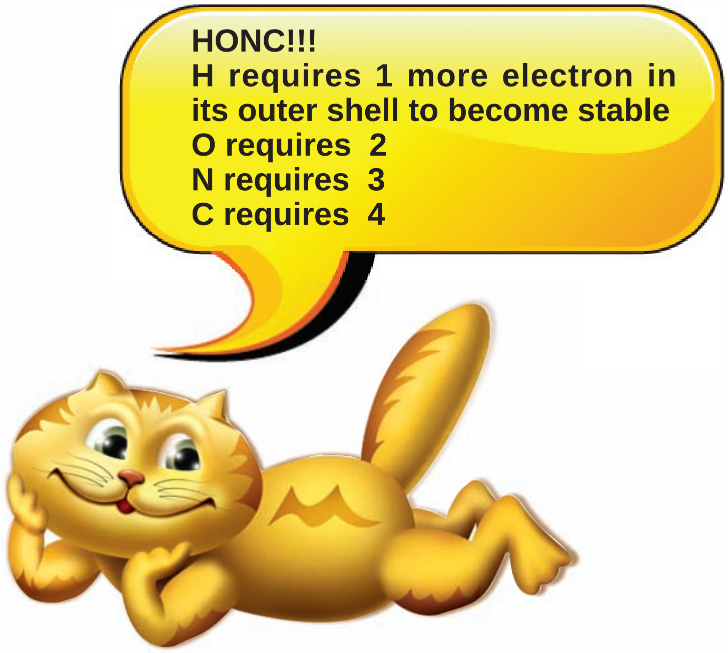
1.1 Overview: The Atoms of Organic Chemistry

Organic chemistry may be defined as the chemistry of the compounds of carbon. Organic chemistry is very important, as living systems are composed mainly of water and organic compounds. Other important organic molecules form essential components of fuels, plastics and other petroleum derivatives.

Carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and the halides (i.e. fluorine - F, chlorine - Cl, bromine - Br, etc.) are the most common atoms found in organic compounds. The atoms in most organic compounds are held together by covalent bonds (*the sharing of an electron pair between two atoms*). Some ionic bonding (*the transfer of electrons from one atom to another*) does exist. Common to both types of chemical bonds is the fact that the atoms bond such that they can achieve the electron configuration of the nearest noble gas, usually eight electrons. This is known as the *octet rule*.

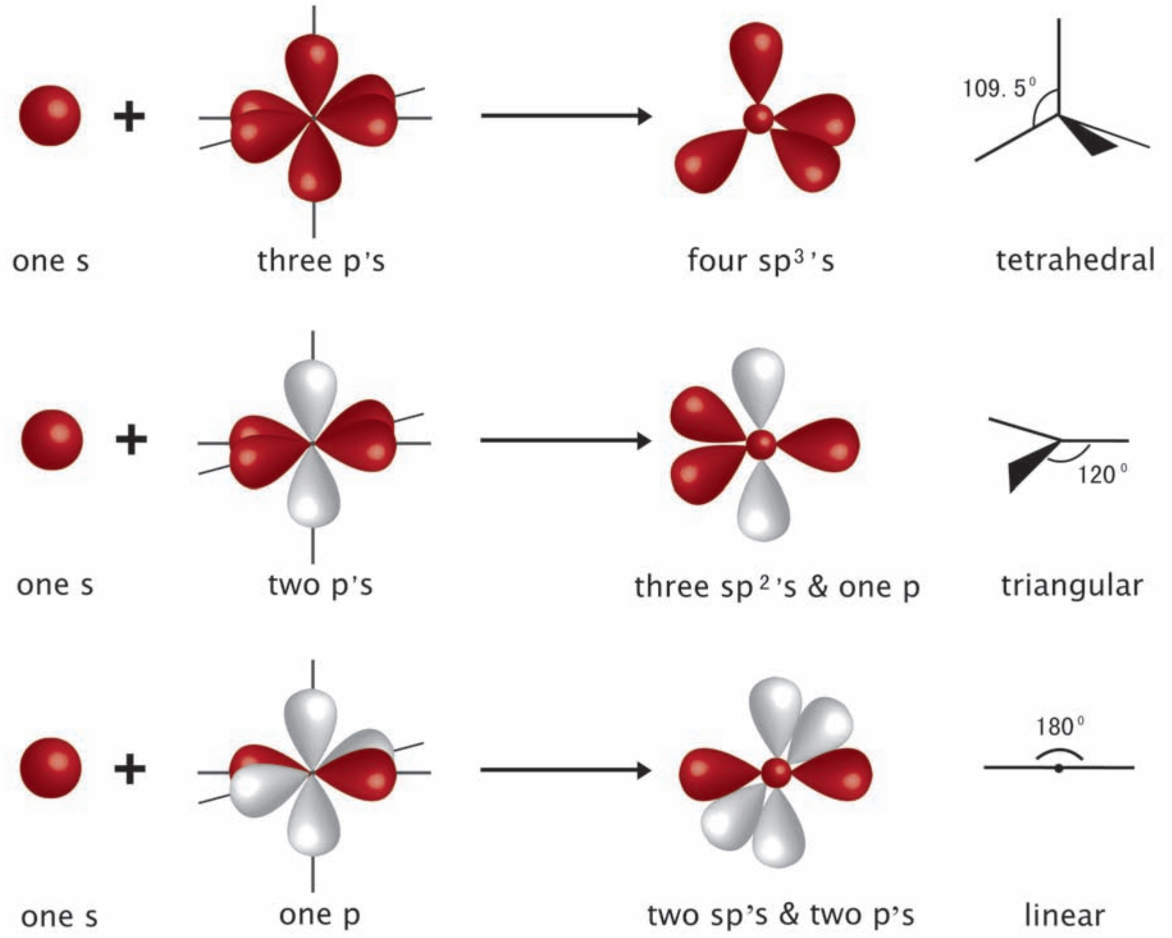
A **carbon** atom has one s and three p orbitals in its outermost shell, allowing it to form 4 single bonds. As well, a carbon atom may be involved in a double bond, where two electron pairs are shared, or a triple bond, where three electron pairs are shared. An **oxygen** atom may form 2 single bonds, or one double bond. It has 2 unshared (lone) electron pairs. A **hydrogen** atom will form only one single bond. A **nitrogen** atom may form 3 single bonds. As well, it is capable of double and triple bonds. It has one unshared electron pair. The **halides** are all able to form only one (single) bond. Halides all have three unshared electron pairs.

Throughout the following chapters we will be examining the structural formulas of molecules involving H, C, N, O, halides and phosphorus (P). However it should be noted that less common atoms often have similar structural formulas within molecules as compared to common atoms. For example, silicon (Si) is found in the same group as carbon in the periodic table; thus they have similar properties. In fact, Si can also form 4 single bonds leading to a tetrahedral structure (i.e. SiH_4, SiO_4). Likewise sulfur (S) is found in the same group as oxygen. Though it can be found as a solid (S_8), it still has many properties similar to those of oxygen. For example, like O in H_2O, sulfur can form a bent, polar molecule which can hydrogen bond (H_2S). We will later see that sulfur is an important component in the amino acid cysteine. {*To learn more about molecular structure, hybrid orbitals, polarity and bonding, review General Chemistry chapters 2 and 3* }


HONC!!!
H requires 1 more electron in its outer shell to become stable
O requires 2
N requires 3
C requires 4

1.2 Hybrid Orbitals

In organic molecules, the orbitals of the atoms are combined to form **hybrid orbitals**, consisting of a mixture of the s and p orbitals. In a carbon atom, if the one s and three p orbitals are mixed, the result is four hybrid sp^3 orbitals. Three hybridized sp^2 orbitals result from the mixing of one s and two p orbitals, and two hybridized sp orbitals result from the mixing of one s and one p. The geometry of the hybridized orbitals is shown in Figure IV.B.1.1.



109. 5°
one s
three p's
four sp^3's
tetrahedral
120°
one s
two p's
three sp^2's & one p
triangular
180°
one s
one p
two sp's & two p's
linear

Figure IV.B.1.1: Hybrid orbital geometry

1.3 Bonding

Sigma (or single) bonds are those in which the electron density is between the nuclei. They are symmetric about the axis, can freely rotate, and are formed when orbitals (regular or hybridized) overlap directly. They are characterized by the fact that they are circular when a cross section is taken and the bond is viewed along the bond axis. The electron density in pi bonds overlaps both above and below the plane of the atoms. A single bond is a sigma bond; a double bond is one sigma and one pi bond; a triple bond is one sigma (σ) and two pi (π) bonds.

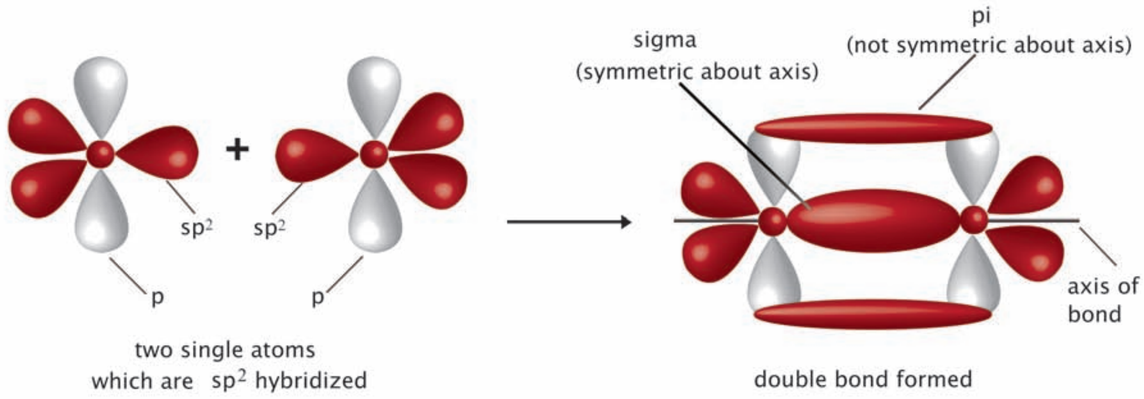

sp2
sp2
p
p
two single atoms which are sp2 hybridized
sigma (symmetric about axis)
pi (not symmetric about axis)
axis of bond
double bond formed

Figure IV.B.1.2: Sigma and pi bonds. The sp^2 hybrids overlap between the nuclei to form a σ bond; the p orbitals overlap above and below the axis between the nuclei to form a π bond.

1.3.1 The Effects of Multiple Bonds

The pi bonds in doubly and triply bonded molecules create a barrier to free rotation about the axis of the bond. Thus multiple bonds create molecules which are much more rigid than a molecule with only a single bond which can freely rotate about its axis.

As a rule, the length of a bond decreases with multiple bonds. For example, the carbon-carbon triple bond is shorter than the carbon-carbon double bond which is shorter than the carbon-carbon single bond.

Bond strength and thus the amount of energy required to break a bond (= *BE, the bond dissociation energy*) varies with the number of bonds. One σ bond has a BE ≈ 110 kcal/mole and one π bond has a BE ≈ 60 kcal/mole. Thus a single bond (one σ) has a BE ≈ 110 kcal/mole while a double bond (one σ + one π) has a BE ≈ 170 kcal/mole. Hence multiple bonds have greater bond strength than single bonds.

1.4 Delocalized Electrons and Resonance

Delocalization of charges in the pi bonds is possible when there are hybridized orbitals in adjacent atoms. This delocalization may be represented in two different ways, the molecular orbital (MO) approach or the resonance (*valence bond*) approach. The differences are found in Figure IV.B.1.3.

The MO approach takes a linear combination of atomic orbitals to form molecular orbitals, in which electrons form the bonds. These molecular orbitals cover the whole molecule, and thus the delocalization of electrons is depicted. In the resonance approach, there is a linear combination of different structures with localized pi bonds and electrons, which together depict the true molecule, or **resonance hybrid**. There is no single structure that represents the molecule.

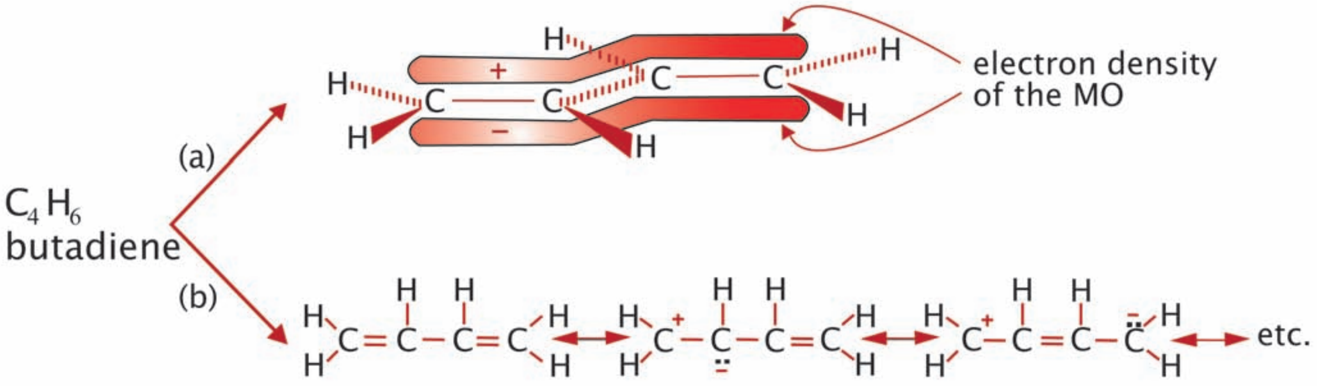
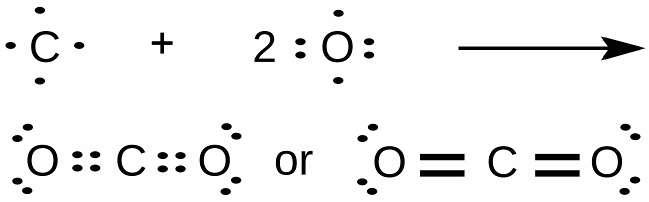


Figure IV.B.1.3: A comparison of MO and resonance approaches. (a) The electron density of the MO covers the entire molecule such that π bonds and p orbitals are not distinguishable. (b) No singular resonance structure accurately portrays butadiene; rather, the true molecule is a composite of all of its resonance structures.

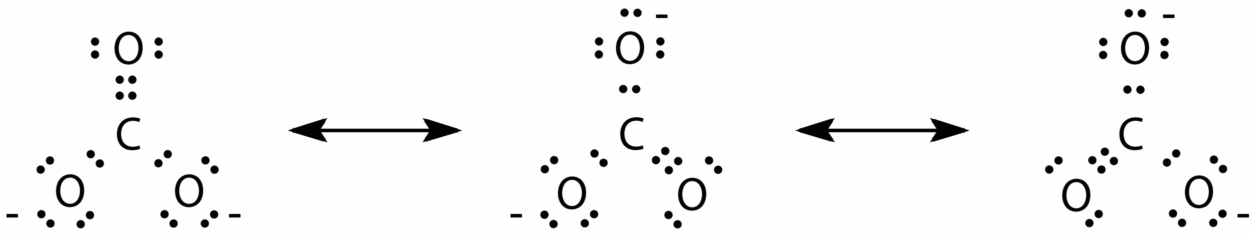
1.5 Lewis Structures, Charge Separation and Dipole Moments

The outer shell (or **valence**) electrons are those that form chemical bonds. **Lewis dot structures** are a method of showing the valence electrons and how they form bonds. These electrons, along with the octet rule (*which states that a maximum of eight electrons are allowed in the outermost shell of an atom*) holds only for the elements in the second row of the periodic table (C,N,O,F). The elements of the third row (Si, P, S, Cl) use d orbitals, and thus can have more than eight electrons in their outer shell.

Let us use CO_2 as an example. Carbon has four valence electrons and oxygen has six. By covalently bonding, electrons are shared and the octet rule is followed,

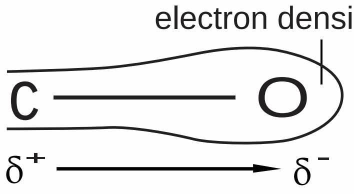


Carbon and oxygen can form resonance structures in the molecule CO_3^{-2}. The -2 denotes two extra electrons to place in the molecule. Once again the octet rule is followed,



In the final structure, each element counts one half of the electrons in a bond as its own, and any unpaired electrons are counted as its own. The sum of these two quantities should equal the number of valence electrons that were originally around the atom.

If the chemical bond is made up of atoms of different electronegativity, there is a **charge separation:**



There is a slight pulling of electron density by the more electronegative atom (oxygen in the preceding example) from the less electronegative atom (carbon in the preceding example). This results in the C-O bond having **partial ionic character** (i.e. *a polar bond; see* CHM 3.3). The charge separation also causes an electrical dipole to be set up in the direction of the arrow. A dipole has a positive end (carbon) and a negative end (oxygen). A dipole will line up in an electric field.

The most electronegative elements (in order, with electronegativities in brackets) are fluorine (4.0), oxygen (3.5), nitrogen (3.0), and chlorine (3.0) [To examine trends, see the periodic table in CHM 2.3]. These elements will often be paired with hydrogen (2.1) and carbon (2.5), resulting in bonds with partial ionic character. The **dipole moment** is a measure of the charge separation and thus, the electronegativities of the elements that make up the bond; the larger the dipole moment, the larger the charge separation.

No dipole moment is found in molecules with no charge separation between atoms (i.e. Cl_2, Br_2), or, when the charge separation is symmetric resulting in a cancellation of bond polarity like vector addition in physics (i.e. CH_4, CO_2).

A molecule where the charge separation between atoms is not symmetric will have a non-zero dipole moment (i.e. CH_3F, H_2O, NH_3 - *see* ORG 11.1.2).

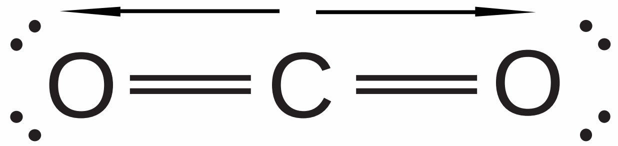


Figure IV.B.1.4: CO_2 - polar bonds but overall it is a non-polar molecule; therefore, CO_2 has a zero dipole moment.

1.5.1 Strength of Polar vs. Non-Polar Bonds

Non-polar bonds are generally stronger than polar covalent and ionic bonds, with ionic bonds being the weakest. However, in compounds with ionic bonding, there is generally a large number of bonds between molecules and this makes the compound as a whole very strong. For instance, although the ionic bonds in one compound are weaker than the non-polar covalent bonds in another compound, the ionic compound's melting point will be higher than the melting point of the covalent compound. Polar covalent bonds have a partially ionic character, and thus the bond strength is usually intermediate between that of ionic and that of non-polar covalent bonds. The strength of bonds generally decreases with increasing ionic character.

1.6 Ground Rules

Opposites attract. Like charges repel. Such simple statements are fundamental in solving over 90% of mechanisms in organic chemistry. Once you are comfortable with the basics - electronegativity, polarity and resonance - you will not need to memorize the grand majority of outcomes of given reactions. You will be capable of quickly deducing the answer even when new scenarios are presented.

A substance which has a formal positive charge ($^+$) or a partial positive charge ("delta$^+$" or δ^+) is attracted to a substance with a formal negative charge ($^-$) or a partial negative charge (δ^-). In general, a substance with a formal charge would have a greater force of attraction than one with a partial charge when faced with an oppositely charged species. There is an important exception: spectator ions. Ions formed by elements in the first two groups of the periodic table (i.e. Na^+, K^+, Ca^{++}) do not actively engage in reactions in organic chemistry. They simply watch the reaction occur then at the very end they associate with the negatively charged product.

In most carbon-based compounds the carbon atom is bonded to a more electronegative atom. For example, in a carbon-oxygen bond the oxygen is δ^- resulting in a δ^+ carbon (*see* ORG 1.5). Because opposites attract, a δ^- carbon (which is unusual) could create a carbon-carbon bond with a δ^+ carbon (which is common). There are two important categories of compounds which can create a carbon-carbon bond; a) alkyl lithiums (RLi) and b) Grignard reagents (RMgBr), because they each have a δ^- carbon. Note that the carbon is δ^- since lithium is to the left of carbon on the periodic table (for electronegativity trends *see* CHM 2.3).

For nucleophiles, the general trend is that the stronger the nucleophile, the stronger the base it is. For example:

$$RO^- > HO^- >> RCOO^- > ROH > H_2O$$

For information on the quality of leaving groups, see ORG 6.2.4.

STEREOCHEMISTRY
Chapter 2

Memorize

- Categories of stereoisomers
- Define enantiomers, diastereomers
- Define ligand, chiral, racemic mixture

Understand

- Basic stereochemistry only

Not Required*

- Advanced level college info
- Assign R/S/E/Z to complex molecules
- Memorize specific rotation equation

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Introduction

Stereochemistry is the study of the relative spatial (3 D) arrangement of atoms within molecules. An important branch of stereochemistry, and most relevant to the GAMSAT, is the study of chiral molecules.

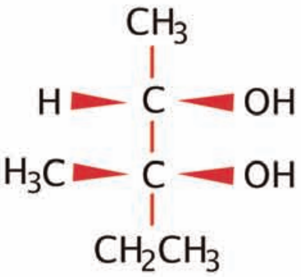
Additional Resources

Free Online Q&A + Forum

Stereochemist-
C=C
CH3
H
CH3

Video: Online or DVD 1

Flashcards



Special Guest

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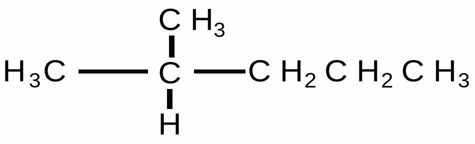
* The real GAMSAT may have advanced level information presented (ie. in a passage) but previous knowledge of said information is not required to answer the questions that would follow. Practice ACER and GS practice GAMSATs can help you clarify this point.

2.1 Isomers

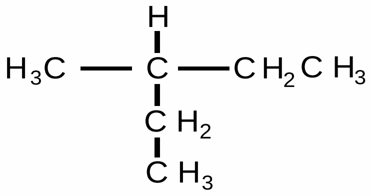
Stereochemistry is the study of the arrangement of atoms in a molecule, in three dimensions. Two *different molecules* with the same number and type of atoms (= *the same molecular formula*) are called isomers. There are several different types of isomers:

Structural isomers have different atoms and/or bonding patterns in relation to each other:



$H_3C-\overset{CH_3}{\underset{H}{C}}-CH_2CH_2CH_3$

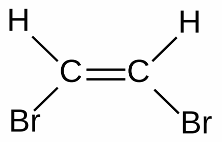
and



$H_3C-\overset{H}{\underset{\underset{CH_3}{CH_2}}{C}}-CH_2CH_3$

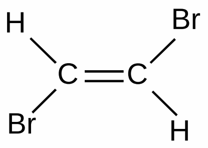
Conformational isomers are isomers which differ only by the rotation about single bonds. As a result, substituents (= *ligands* = *attached atoms or groups*) can be maximally close (*eclipsed conformation*), maximally apart (*anti or staggered conformation*) or anywhere in between (i.e. *gauche conformation*). Though all conformations occur at room temperature, anti is most stable since it minimizes electron shell repulsion.

Geometric isomers occur because carbons that are in a ring or double bond structure are *unable* to freely rotate. Geometric isomers occur only as alkenes and cyclic compounds. This results in *cis* and *trans* compounds. When the substituents (i.e. Br) are on the same side of the ring or double bond, it is designated cis. When they are on opposite sides, it is designated trans. The trans isomer is more stable since the substituents are further apart, thus electron shell repulsion is minimized.



cis-dibromoethene

and



trans-dibromoethene

In general, structural and geometric isomers have different reactivity, spectra and physical properties (i.e. boiling points, melting points, etc.).

Stereoisomers are different compounds with the same structure, differing only in the spatial orientation of the atoms (= *configuration*). Stereoisomers may be further divided into enantiomers and diastereomers.

2.2 Enantiomers and Diastereomers

Enantiomers come in pairs. They are two non-superimposable molecules, which are mirror images of each other. In order to have an enantiomer, a molecule must be chiral. Chiral molecules contain a carbon atom that has four different substituents attached to it.

Enantiomers have the same chemical and physical properties. The only difference is with their interactions with other chiral molecules, and their rotation of plane polarized light.

Conversely, diastereomers are any pair of stereoisomers that are not enantiomers. Diastereomers are both chemically and physically different from each other.

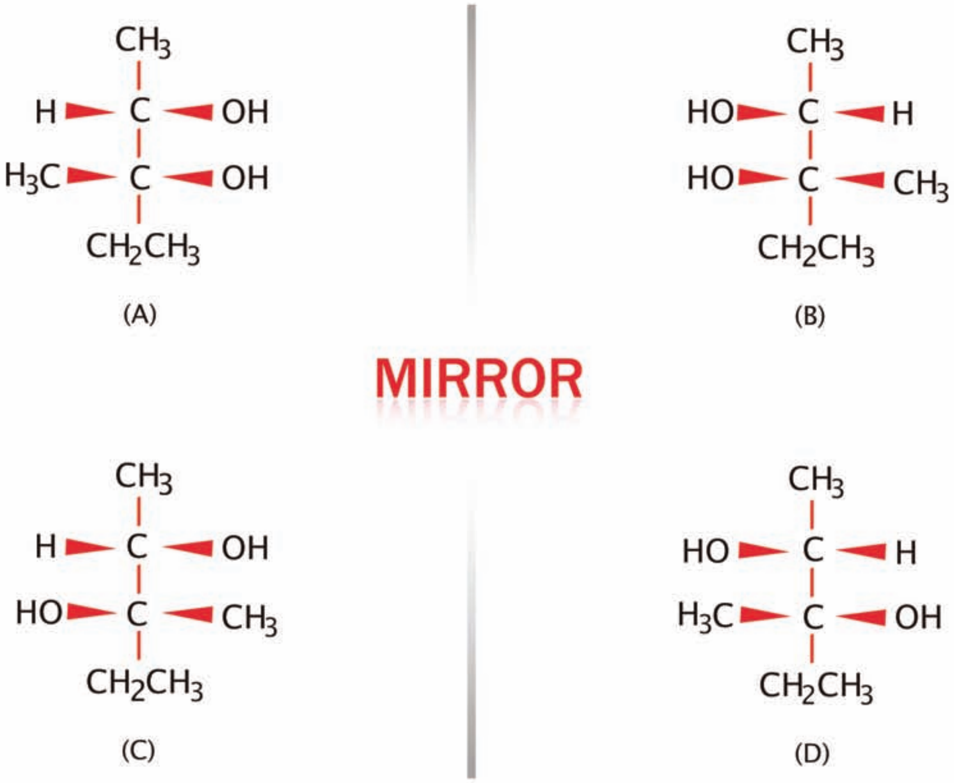


Figure IV.B.2.1: Enantiomers and diastereomers. The enantiomers are A & B, C & D. The diastereomers are A & C, A & D, B & D, B & C.

2.3 Absolute and Relative Configuration

Before 1951, the absolute three dimensional arrangement or configuration of chiral molecules was not known. Instead chiral molecules were compared to an arbitrary standard (*glyceraldehyde*). Thus the *relative* configuration could be determined. Once the actual spatial arrangements of groups in molecules were finally determined, the *absolute* configuration could be known.

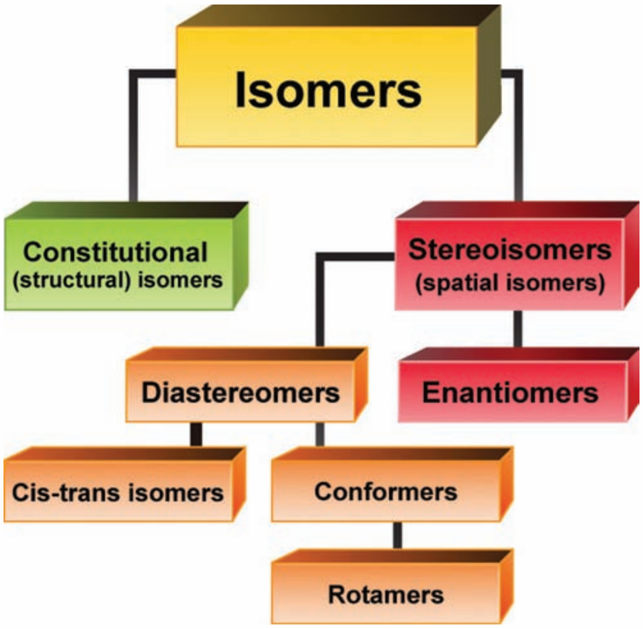

Isomers
Constitutional (structural) isomers
Stereoisomers (spatial isomers)
Diastereomers
Enantiomers
Cis-trans isomers
Conformers
Rotamers

Figure IV.B.2.1.1: Categories of isomers

2.3.1 The R, S System

One consequence of the existence of enantiomers, is a special system of nomenclature: the R, S system. This system provides information about the absolute configuration of a molecule. This is done by assigning a stereochemical configuration at each asymmetric (*chiral*) carbon in the molecule by using the following steps:

1. Identify an asymmetric carbon, and the four attached groups.

2. Assign priorities to the four groups, using the following rules:

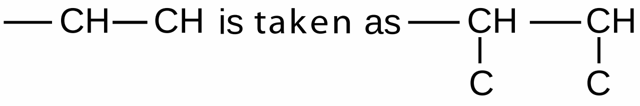
i. Atoms of higher atomic number have higher priority.

ii. An isotope of higher atomic mass receives higher priority.

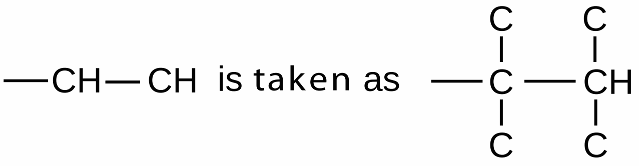
iii. The higher priority is assigned to the group with the atom of higher atomic number or mass at the first point of difference.

iv. If the difference between the two groups is due to the number of otherwise identical atoms, the higher priority is assigned to the group with the greater number of atoms of higher atomic number or mass.

v. To assign priority of double and triple bonded groups, these atoms are replicated:



$-CH-CH$ is taken as $-\underset{\overset{|}{C}}{CH}-\underset{\overset{|}{C}}{CH}$

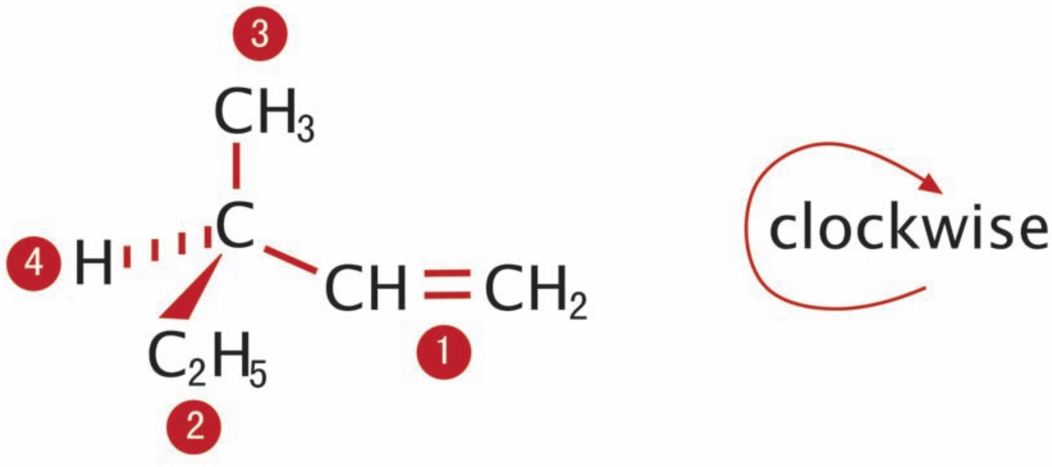


$-CH-CH$ is taken as $-\overset{\underset{|}{C}}{\underset{\overset{|}{C}}{C}}-\overset{\underset{|}{C}}{\underset{\overset{|}{C}}{CH}}$

3. View the molecule along the bond from the asymmetric carbon to the group of lowest priority (i.e. the asymmetric carbon is near, and the low priority group is far away).

4. Consider the clockwise or counterclockwise order of the priorities of the remaining groups. If they increase in a clockwise direction, the asymmetric carbon is said to have the R configuration. If they decrease in a clockwise direction, the asymmetric carbon is said to have the S configuration.

A stereoisomer is named by indicating the configurations of each of the asymmetric carbons.



(R) - 3 - methyl - 1 - pentene

Figure IV.B.2.2: Assigning Absolute Configuration. In organic chemistry, the directions of the bonds are symbolized as follows: a broken line extends away from the viewer (i.e. INTO the page), a solid triangle projects towards the viewer, and a straight line extends in the plane of the paper. According to rule #3, we must imagine that the lowest priority group (H) points away from the viewer.

2.3.2 Optical Isomers and the D, L System

Optical Isomers are stereoisomers that differ by different spatial orientations about a chiral carbon atom.Light is an electromagnetic wave that contains oscillating fields. In ordinary light, the electric field oscillates in all directions. However, it is possible to obtain light with an electric field that oscillates in only one plane. This type of light is known as **plane polarized light**. When plane polarized light is passed through a sample of a chiral substance, it will emerge vibrating in a different plane than it started.Optical isomers differ only in this rotation. If the light is rotated in a clockwise direction, the compound is dextrorotary, and is designated by a D or (+). If the light is rotated in a counterclockwise direction, the compound is levrorotary, and is designated by an L or (-). All L compounds have the same relative configuration as L-glyceraldehyde.

A racemic mixture will show no rotation of plane polarized light. This is a consequence of the fact that a racemate is a mixture with equal amounts of the D and L forms of a substance.

Specific rotation (α) is an inherent physical property of a molecule. It is defined as follows:

$$\alpha = \frac{\textbf{Obesrved rotation in degrees}}{\textbf{(tube legth in dm) (concentration in g/ml)}}$$

The observed rotation is the rotation of the light passed through the substance. The tube length is the length of the tube that contains the sample in question. The specific rotation is dependent on the solvent used, the temperature of the sample, and the wavelength of the light.

It should be noted that there is no clear correlation between the absolute configuration (i.e. R, S) and the direction of rotation of plane polarized light.

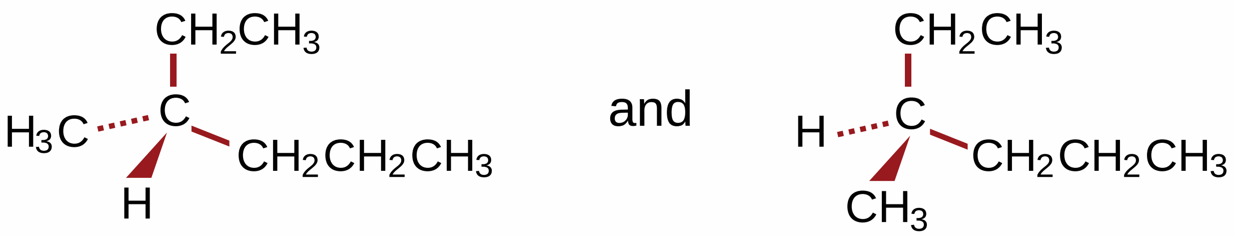
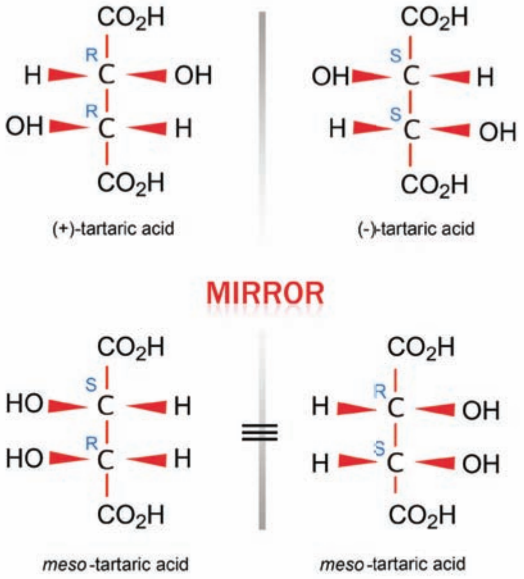


Figure IV.B.2.3: Optical isomers.

2.3.3 Meso Compounds

Tartaric acid (= 2,3-dihydroxybutanedioic acid which, for GAMSAT purposes, please feel free to forget its IUPAC name!) has two chiral centers that have the same four substituents and are equivalent. As a result, two of the four possible stereoisomers of this compound are identical due to a plane of symmetry. Thus there are only three stereoisomeric tartaric acids. Two of these stereoisomers are enantiomers and the third is an achiral diastereomer, called a *meso* compound. Meso compounds are achiral (optically inactive) diastereomers of chiral stereoisomers {**M**e**S**o = **M**irror of **S**ymmetry}.



(+)-tartaric acid (-)-tartaric acid

meso-tartaric acid *meso*-tartaric acid

2.3.4 E, Z Designation

The E, Z notation is the IUPAC preferred method for designating the stereochemistry of double bonds. ORG 2.1 reviewed how to use cis/trans. The E, Z notation is quite similar but more precise.

To begin with, each substituent at the double bond is assigned a priority (see 2.3.1 for rules). If the two groups of higher priority are on opposite sides of the double bond, the bond is assigned the configuration E, (from *entgegen*, the German word for "opposite"). If the two groups of higher priority are on the same side of the double bond, the bond is assigned the configuration Z, (from *zusammen,* the German word for "together"). {Learning German is NOT required for the GAMSAT!}