

## Chapter 24. The Chemistry of Life: Organic and Biological Chemistry

### Common Student Misconceptions

- Students will often find the distinction between organic and inorganic molecules as somewhat vague. As a rule of thumb, inorganic carbon is carbon that is *not* bound to hydrogen, for example,  $\text{H}_2\text{CO}_3$ .
- Students interpret straight chain to mean geometrically linear. They need to be reminded of the tetrahedral C atom from VSEPR theory.
- Students often think that chirality is only possible for organic compounds, and that chiral centers are limited to C atoms.
- Many students think that one cannot have aqueous reactions involving organic compounds.
- Students are surprised that, in organic chemistry, acid-base reactions are more often viewed as an electron pair transfer from a Lewis base to a Lewis acid instead of a proton transfer from a B-L acid to a B-L base.
- Students are surprised that the  $-\text{OH}$  (hydroxyl) group in organic chemistry is not the same as the  $\text{OH}^-$  ion in ionic compounds, such as metal hydroxides.

### Teaching Tips

- Students should be encouraged to follow the chapter links to review earlier material as they progress through this chapter.
- In particular, students should review Lewis structures as well as Lewis acids and bases.
- Students should be encouraged to draw and re-draw structures of organic compounds.

## Lecture Outline

### 24.1 General Characteristics of Organic Molecules

- **Organic chemistry** is the branch of chemistry that studies carbon compounds.
- **Biochemistry**, *biological chemistry*, or *chemical biology* is the study of the chemistry of living things.

#### The Structures of Organic Molecules<sup>1,2,3</sup>

- The shapes of organic and biochemical molecules are important in determining their physical and chemical properties.
- Consider the element carbon:
  - Using the VSEPR model we find that the bonds to carbon involve four electron pairs.
    - The electron pairs are in a tetrahedral arrangement when all four bonds are single bonds.
      - The carbon is  $sp^3$  hybridized.
    - A carbon with one double bond shows a trigonal arrangement.
      - The carbon is  $sp^2$  hybridized.
    - If the carbon has a triple bond, the arrangement is linear.
      - The carbon is  $sp$  hybridized.
- C–H bonds occur in almost every organic molecule.

<sup>1</sup> “Methane” 3-D Model from Instructor’s Resource CD/DVD

<sup>2</sup> “Acetonitrile” 3-D Model from Instructor’s Resource CD/DVD

<sup>3</sup> Figure 24.1 from Transparency Pack

- Carbon-carbon bonds for the *backbone* or *skeleton* of the molecule and the H atoms are on the *surface* of the molecule.

### The Stabilities of Organic Substances

- The stability of organic substances varies.
- Substances such as benzene have a special stability due to the delocalization of  $\pi$  electrons.
- A group of atoms that determines how an organic molecule functions or reacts is a **functional group**.
  - Functional groups are the center of reactivity in organic molecules.
    - This group of atoms determines how an organic molecule reacts or *functions*.

### Solubility and Acid-Base Properties of Organic Substances<sup>4,5</sup>

- The most common bonds in organic substances are carbon-carbon bonds.
  - This results in a low overall polarity of many organic molecules.
    - Such molecules are soluble in nonpolar solvents.
- Organic substances that are soluble in water and other polar solvents have polar groups.
  - Examples: glucose and ascorbic acid (vitamin C).
- Soaps and detergents are examples of molecules that have both a polar part (which is water soluble) and a nonpolar part (which is soluble in nonpolar substances such as fat).
  - They function as *surfactants*.
- Many organic molecules contain acidic or basic groups.
  - Carboxylic acids contain the functional group  $-\text{COOH}$ .
  - Amines are important organic bases.
    - They contain the functional groups  $-\text{NH}_2$ ,  $-\text{NHR}$ , or  $-\text{NR}_2$ .
    - “R” groups are groups consisting of carbon-carbon and carbon-hydrogen bonds.
- Some molecules contain both an acidic and a basic group.

## 24.2 Introduction to Hydrocarbons<sup>6,7,8,9,10,11,12,13</sup>

- The simplest class of organic molecules is the *hydrocarbons*.
  - Hydrocarbons consist only of carbon and hydrogen.
  - There are four major classes of hydrocarbons: alkanes, alkenes, alkynes, and aromatics.
- **Alkanes** contain only single bonds.
  - These compounds are also called *saturated hydrocarbons* because they have the largest possible number of hydrogen atoms per carbon.
  - An example is ethane ( $\text{C}_2\text{H}_6$ ).
- **Alkenes** contain at least one carbon-carbon double bond.
  - They are also called *olefins*.
  - An example is ethylene ( $\text{C}_2\text{H}_4$ ).
- **Alkynes** contain a carbon-carbon triple bond.
  - An example is acetylene ( $\text{C}_2\text{H}_2$ ).

<sup>4</sup> “Glucose” 3-D Model from Instructor’s Resource CD/DVD

<sup>5</sup> “Sodium Stearate” 3-D Model from Instructor’s Resource CD/DVD

<sup>6</sup> Table 24.1 from Transparency Pack

<sup>7</sup> “Ethane” 3-D Model from Instructor’s Resource CD/DVD

<sup>8</sup> “Propane” 3-D Model from Instructor’s Resource CD/DVD

<sup>9</sup> “Ethene (ethylene)” 3-D Model from Instructor’s Resource CD/DVD

<sup>10</sup> “Ethyne (acetylene)” 3-D Model from Instructor’s Resource CD/DVD

<sup>11</sup> “Benzene” 3-D Model from Instructor’s Resource CD/DVD

<sup>12</sup> “Boiling Point” Activity from Instructor’s Resource CD/DVD

<sup>13</sup> “Alkanes: Abundant, Pervasive, Important, and Essential” from Further Readings

- **Aromatic hydrocarbons** have carbon atoms connected in a planar ring structure.
  - The carbons are linked by both  $\sigma$  and  $\pi$  bonds.
  - The best known example is benzene ( $C_6H_6$ ).
- Alkenes, alkynes, and aromatic hydrocarbons are all examples of *unsaturated hydrocarbons*.
- The name of the alkane varies according to the number of C atoms present in the chain.
- We can make a table of members of a homologous series of straight-chain alkanes.
  - In this table, each member differs by one  $CH_2$  unit.
  - The names each end in -ane.
  - The prefix assigned indicates the number of carbon atoms.
    - Example:  $CH_4$  is the alkane with a single carbon atom; it is called *methane*.
    - The next member of the series is  $C_2H_6$ , with two carbon atoms; it is called *ethane*.
- The formulas for alkanes may be written in a notation called *condensed structural formulas*.
  - This notation shows which atoms are bonded to one another, but does not require that we draw in all of the bonds.
  - Notice that each carbon in an alkane has four single bonds.

### Structures of Alkanes<sup>14</sup>

- VSEPR theory predicts each C atom is tetrahedral.
  - Therefore, each C atom has  $sp^3$ -hybridized orbitals.
  - Rotation about the C–C bond in alkanes is relatively easy.

### Structural Isomers<sup>15,16,17,18,19</sup>

- In *straight-chain hydrocarbons*, the C atoms are joined in a continuous chain.
  - In a straight-chain hydrocarbon, no one C atom may be attached to more than two other C atoms.
  - Straight chain hydrocarbons are not linear.
    - Each C atom is tetrahedral, so the chains are bent.
- *Branched-chain hydrocarbons* are possible for alkanes with four or more C atoms.
  - Structures with different branches can be written for the same formula.
    - **Structural isomers** are compounds with the same molecular formula but different bonding arrangements.
    - Structural isomers have somewhat different physical and chemical properties.

### Nomenclature of Alkanes<sup>20,21,22,23,24,25</sup>

- Organic compounds are named according to rules established by the International Union for Pure and Applied Chemistry (IUPAC).
- To name alkanes:
  - Find the longest chain and use it as the base name of the compound.

<sup>14</sup> Figure 24.3 from Transparency Pack

<sup>15</sup> Figure 24.4 from Transparency Pack

<sup>16</sup> “Butane” 3-D Model from Instructor’s Resource CD/DVD

<sup>17</sup> “Methylpropane (isobutane)” 3-D Model from Instructor’s Resource CD/DVD

<sup>18</sup> “Pentane” 3-D Model from Instructor’s Resource CD/DVD

<sup>19</sup> “Neopentane (dimethylpropane)” 3-D Model from Instructor’s Resource CD/DVD

<sup>20</sup> “Nomenclature of Alkanes” Activity from Instructor’s Resource CD/DVD

<sup>21</sup> Table 24.4 from Transparency Pack

<sup>22</sup> “The IUPAC Rules for Naming Organic Molecules” from Further Readings

<sup>23</sup> “Why is ‘R’ Used to Symbolize Hydrocarbon Substituents?” from Further Readings

<sup>24</sup> “A Simple Method of Drawing Stereoisomers from Complicated Symmetrical Structures” from Further Readings

<sup>25</sup> “Condensed Structural Formula” Activity from Instructor’s Resource CD/DVD

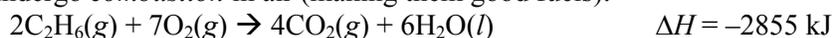
- Groups attached to the main chain are called *substituents*.
- Number the carbon atoms in the longest chain starting with the end closest to a substituent.
  - The preferred numbering will give substituents the lowest numbers.
- Name and give the location of each substituent.
  - A substituent group formed by removing an H atom from an alkane is called an **alkyl group**.
  - Alkyl groups are named by replacing the *-ane* ending with *-yl*.
    - Example: CH<sub>4</sub> is *methane* and a –CH<sub>3</sub> group is a *methyl* group.
- When two or more substituents are present, list them in alphabetical order.
  - When there are two or more of the same substituent, the number of that type of substituent is indicated by a prefix: (i.e., “dimethyl” indicates two methyl group substituents).

### Cycloalkanes

- Alkanes that form rings are called **cycloalkanes**.
- Cyclopropane and cyclobutane are strained because the C–C–C bond angles in the ring are less than the 109.5° required for a tetrahedral geometry.
  - Because of the strain in the ring, cyclopropane is very reactive.

### Reactions with Alkanes<sup>26</sup>

- The C–C and C–H bonds are very strong.
  - Therefore, alkanes are very unreactive.
- At room temperature alkanes, do not react with acids, bases, or strong oxidizing agents.
- Alkanes do undergo *combustion* in air (making them good fuels):



## 24.3 Alkenes, Alkynes, and Aromatic Hydrocarbons

- Alkanes contain the largest possible number of hydrogen atoms per carbon atom; they are called *saturated hydrocarbons*.
- Alkenes, alkynes, and aromatic hydrocarbons contain less hydrogens than an alkane with the same number of carbon atoms.
  - They are called *unsaturated hydrocarbons*.
  - They tend to be more reactive than unsaturated hydrocarbons.

### Alkenes<sup>27</sup>

- Alkenes are unsaturated hydrocarbons that contain C and H atoms and at least one C=C double bond.
- The simplest alkenes are H<sub>2</sub>C=CH<sub>2</sub> (ethene) and CH<sub>3</sub>CH=CH<sub>2</sub> (propene).
  - Their common names are ethylene and propylene.
- Alkenes are named in the same way as alkanes with the suffix *-ene* replacing the *-ane* in alkanes.
  - The location of the double bond is indicated by a number.
  - If a substance has two or more double bonds, the number of double bonds is indicated with a prefix.
- **Geometric isomers** are possible in alkenes since there is no rotation about a C=C π bond.
  - Note that the overlap between orbitals is above and below the plane of the σ bonds.
  - As the C–C bond begins to rotate (moving from *cis* to *trans*) the overlap decreases.
  - At 90°, the π bond breaks completely.
    - Therefore, there is no “free” rotation about a π bond.
  - Therefore, *cis* and *trans* isomers do not readily interconvert.

### Alkynes

- Alkynes are hydrocarbons with one or more C≡C bond.

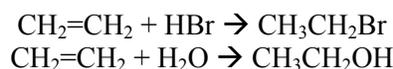
<sup>26</sup> “Chloromethane” 3-D Model from Instructor’s Resource CD/DVD

<sup>27</sup> “*Trans*-2-butene” 3-D Model from Instructor’s Resource CD/DVD

- The triple bond has one  $\sigma$  and two  $\pi$  bonds between two C atoms.
- Ethyne (acetylene) is the simplest alkyne:  $\text{HC}\equiv\text{CH}$ .
- Alkynes are named in the same way as alkenes with the suffix *-yne* replacing the *-ene* for alkenes.

### Addition Reactions of Alkenes and Alkynes<sup>28,29,30,31,32</sup>

- The dominant reactions for alkenes and alkynes are **addition reactions**.
  - They involve the addition of something to the two atoms that form the double or triple bond.
    - Example: The addition of a halogen (bromine) to ethylene:
 
$$\text{H}_2\text{C}=\text{CH}_2 + \text{Br}_2 \rightarrow \text{H}_2\text{BrC}-\text{CBrH}_2$$
    - Note that the C–C  $\pi$  bond has been replaced by two C–Br  $\sigma$  bonds.
  - A common addition reaction is *hydrogenation*:
 
$$\text{CH}_3\text{CH}=\text{CHCH}_3 + \text{H}_2 \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_3$$
  - Hydrogenation requires high temperatures and pressures as well as the presence of a catalyst (e.g., finely divided metals such as Ni, Pt, Pd).
  - Note that the alkene is converted to an alkane.
- Another common addition reaction involves the addition of hydrogen halides or water across the  $\pi$  bond:



- Alkynes are also capable of addition reactions.

### Aromatic Hydrocarbons<sup>33</sup>

- Aromatic structures are formally related to benzene ( $\text{C}_6\text{H}_6$ ).
  - Many aromatic compounds are given common names (e.g., naphthalene, toluene, anthracene).

### Stabilization of $\pi$ Electrons by Delocalization

- Benzene is a planar symmetrical molecule.
- The delocalized  $\pi$  electrons are usually represented as a circle in the center of the ring.

### Substitution Reactions

- Benzene is not reactive because of the stability associated with the delocalized  $\pi$  electrons.
- Even though they contain  $\pi$  bonds, aromatic hydrocarbons undergo **substitution reactions** more readily than addition reactions.
  - In a substitution reaction, one atom of a molecule is removed and replaced or substituted by another atom or group of atoms.
  - Example: If benzene is treated with nitric acid in the presence of sulfuric acid (catalyst), nitrobenzene is produced.
    - Under some conditions, more than one nitro group may be added to the benzene.
    - If two nitro groups are added, three possible isomers may be formed: *-ortho-*, *-meta-*, and *-para-*dinitrobenzene.
  - Another type of substitution reaction is a *Friedel-Crafts reaction* in which alkyl groups can be substituted onto an aromatic ring by reaction with an alkyl halide in the presence of aluminum chloride (catalyst).

<sup>28</sup> “Addition Reactions of Alkenes” Activity from Instructor’s Resource CD/DVD

<sup>29</sup> “Surface Reaction-Hydrogenation” Animation from Instructor’s Resource CD/DVD

<sup>30</sup> “Testing for Unsaturated Hydrocarbons with Bromine” Movie from Instructor’s Resource CD/DVD

<sup>31</sup> Figure 24.8 from Transparency Pack

<sup>32</sup> “Hydrogen Chloride” 3-D Model from Instructor’s Resource CD/DVD

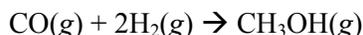
<sup>33</sup> “The Origins of the Ortho-, Meta-, and Para- Prefixes in Chemical Nomenclature” from Further Readings

## 24.4 Organic Functional Groups

- Hydrocarbons are relatively unreactive.
- For an organic molecule to be reactive it needs something additional.
- A site of reactivity in an organic molecule is called a *functional group*. Functional groups determine the chemistry of a molecule.
- The simplest functional groups are  $\pi$  electrons.
  - C=C double bonds and C≡C triple bonds are functional groups.
- Other functional groups contain elements other than C or H.
- Chemists usually use R, R', R'', etc., to represent alkyl groups.

### Alcohols<sup>34,35</sup>

- **Alcohols** are derived from hydrocarbons and contain –OH (*hydroxyl* or *alcohol*) groups.
- The names are derived from the hydrocarbon name with *-ol* replacing the *-ane* suffix.
  - Example: *ethane* becomes *ethanol*.
- Because the O–H bond is polar and can participate in hydrogen bonding, alcohols are more water soluble than alkanes.
- Consider the properties of some representative alcohols:
  - CH<sub>3</sub>OH, methanol, is used as a gasoline additive and a fuel.
    - Methanol is produced by the reaction of CO with hydrogen under high pressure and high temperature:



- Ethanol is produced by the fermentation of carbohydrates.
  - Ethanol is the alcohol found in alcoholic beverages.
- Polyhydroxy alcohols (polyols) contain more than one –OH group per molecule (e.g., ethylene glycol used as antifreeze).
- Aromatic alcohols can also be formed (e.g., phenol).
  - Note that aromatic alcohols are weak acids.
- Cholesterol is a physiologically important alcohol.

### Ethers

- Compounds in which two hydrocarbons are linked by an oxygen are called **ethers**.
- Ethers can be formed by a dehydration reaction:
 
$$\text{CH}_3\text{CH}_2\text{-OH} + \text{H-OCH}_2\text{CH}_3 \rightarrow \text{CH}_3\text{CH}_2\text{-O-CH}_2\text{CH}_3 + \text{H}_2\text{O}$$
  - This *condensation reaction* involves the removal of a water molecule from two molecules of alcohol.
- Ethers are commonly used as solvents.
  - Common examples are diethyl ether and tetrahydrofuran (a cyclic ether).

### Aldehydes and Ketones<sup>36,37,38</sup>

- The **carbonyl group** is C=O.
- The carbonyl group plus the type of atoms attached to the carbonyl carbon defines the particular kind of compound.
- **Aldehydes** must have at least one H atom attached to the carbonyl C:
 
$$\text{R-CHO}$$
- **Ketones** must have two C atoms attached to the carbonyl C:

<sup>34</sup> “Oxidation of Alcohol by Mn<sub>2</sub>O<sub>7</sub>” from Live Demonstrations

<sup>35</sup> “Methanol” 3-D Model from Instructor’s Resource CD/DVD

<sup>36</sup> “The Disappearing Coffee Cup” from Live Demonstrations

<sup>37</sup> “Ethanal (acetaldehyde)” 3-D Model from Instructor’s Resource CD/DVD

<sup>38</sup> “Propanone (acetone)” 3-D Model from Instructor’s Resource CD/DVD



- Aldehydes and ketones are prepared by the oxidation of alcohols.
- Ketones are less reactive than aldehydes and are used as solvents.
  - Two common examples of ketones are acetone and methyl ethyl ketone (MEK).
- Other examples of molecules that contain aldehydes or ketones are vanilla and cinnamon flavorings. The ketones carvone and camphor are responsible for the flavors of spearmint and caraway, respectively.

### Carboxylic Acids and Esters<sup>39,40,41,42,43,44</sup>

- Carboxylic acids** contain a carbonyl group with an –OH attached.
- The *carboxyl* functional group is –COOH:



- Common names of carboxylic acids reflect their origins (e.g., formic acid was first extracted from ants, the Latin *formica* means “ant”).
- Carboxylic acids are generally weak acids.
  - Typical carboxylic acids are found in spinach (oxalic acid), vinegar (acetic acid), vitamin C (ascorbic acid), aspirin (acetylsalicylic acid), and citrus fruits (citric acid).
- Carboxylic acids can be prepared by oxidizing alcohols that contain a –CH<sub>2</sub>OH group.
  - Example: Oxidation of ethanol (CH<sub>3</sub>CH<sub>2</sub>OH) to acetic acid (CH<sub>3</sub>COOH) is responsible for the souring of wines.
- Acetic acid can be prepared by reacting methanol with CO in the presence of a catalyst.
  - This kind of reaction is called *carbonylation*.
- Esters** can be prepared by condensation reactions involving a carboxylic acid and an alcohol; the products are the ester and water.
- Esters contain –COOR groups:



- Esters are named using the alcohol part first and then the acid part.
  - Example: The ester formed from ethanol and acetic acid is ethyl acetate.
- Esters tend to have very pleasant characteristic odors and are often used as food flavorings and scents.
  - Some common esters are benzocaine (used in some sunburn lotions), ethyl acetate (a component of some nail polish removers), vegetable oils, polyester thread, and aspirin.
- In the presence of a base, esters hydrolyze (the molecule splits into acid and alcohol).
  - Saponification** is the **hydrolysis** of an ester in the presence of a base.
  - This process is used in the production of soaps from animal fats or vegetable oils.
    - Soap is made by heating fats or oils in a strong base (NaOH).
      - The long-chain carboxylic acid and alcohol components of the fats are released.
      - The soap made from this process consists of sodium salts of the long-chain carboxylic acids called fatty acids.
      - Using potassium hydroxide produces soft or liquid soaps.

### Amines and Amides<sup>45,46</sup>

- Amines* are organic bases.

<sup>39</sup> “A Miracle Drug” from Further Readings

<sup>40</sup> “Ester, What’s in My Food?” from Further Readings

<sup>41</sup> “Making Canned Heat” from Live Demonstrations

<sup>42</sup> “Trans Fatty Acids” from Further Readings

<sup>43</sup> “Ethanoic Acid (acetic acid)” 3-D Model from Instructor’s Resource CD/DVD

<sup>44</sup> “Ethyl Ethanoate (ethyl acetate)” 3-D Model from Instructor’s Resource CD/DVD

<sup>45</sup> “Ethanamine (ethylamine)” 3-D Model from Instructor’s Resource CD/DVD

<sup>46</sup> “Ethanamide” 3-D Model from Instructor’s Resource CD/DVD

- Just as alcohols can be thought of as organic forms of water, amines can be thought of as organic forms of ammonia.
  - They have the general formula  $R_3N$  where R may be either H or a hydrocarbon group.
    - Examples of organic amines are ethylamine ( $CH_3CH_2NH_2$ ), triethylamine [ $(CH_3)_3N$ ], and aniline ( $C_6H_5-NH_2$ ).
- Amides are composites of carbonyl and amine functionalities.

## 24.5 Chirality in Organic Chemistry<sup>47,48,49,50,51,52,53,54,55</sup>

- Recall that molecules whose mirror images are nonsuperimposable are **chiral**.
  - Compounds containing carbon atoms with four different attached groups are inherently chiral.
- Chemists use the labels *R*- and *S*- to distinguish between these *enantiomers*.
  - The physical properties of enantiomers are generally identical.
  - Enantiomers have identical chemical properties if the molecules are reacting with reagents that are nonchiral.
    - Enantiomers exhibit different chemical properties in a chiral environment.
- A mixture of two enantiomers present in the same quantity is called a *racemic* mixture.
- Some molecules have more than one chiral center.
  - Examples include tartaric acid (found as crystalline deposits in wine) and some of the amino acids found in proteins.

## 24.6 Introduction of Biochemistry<sup>56,57</sup>

- The biosphere is the part of the Earth containing living organisms.
- Biochemical molecules tend to be very large and difficult to synthesize.
- Organisms build biochemical molecules from the smaller molecules available in the biosphere.
- Living organisms are highly ordered.
  - Therefore, living organisms have very low entropy.
  - Living systems must continually resist the tendency to become less ordered!
- Many biologically important molecules are polymers, called **biopolymers**.
- Biopolymers fall into three broad classes:
  - proteins,
  - polysaccharides (carbohydrates), and
  - nucleic acids.

## 24.7 Proteins

### Amino Acids<sup>58,59</sup>

<sup>47</sup> “The World’s First ‘Pastarimeter’: An Analogous Demonstration of Polarimetry Using Pasta *Fusilli*” from Live Demonstrations

<sup>48</sup> “Chirality” Animation from Instructor’s Resource CD/DVD

<sup>49</sup> Figure 24.15 from Transparency Pack

<sup>50</sup> “Optical Activity” Animation from Instructor’s Resource CD/DVD

<sup>51</sup> “Demonstration of Enantiomer Specificity of Proteins and Drugs” from Live Demonstrations

<sup>52</sup> “2-chlorobutane” 3-D Model from Instructor’s Resource CD/DVD

<sup>53</sup> “2-bromopentane” 3-D Model from Instructor’s Resource CD/DVD

<sup>54</sup> “Albuterol” 3-D Model from Instructor’s Resource CD/DVD

<sup>55</sup> “Ibuprofen” 3-D Model from Instructor’s Resource CD/DVD

<sup>56</sup> “Icie Macy Hoobler: Pioneer Woman Biochemist” from Further Readings

<sup>57</sup> “Why Teach Biochemistry?” from Further Readings

<sup>58</sup> “Proteins and Amino Acids” Animation from Instructor’s Resource CD/DVD

- **Proteins** are macromolecules present in all cells.
- They are made up of building blocks called  **$\alpha$ -amino acids**.
- At normal physiological pH, amino acids are present in aqueous solution as the doubly ionized forms called *zwitterions*.
  - A zwitterion has both positive and negative charges in one molecule.
    - The carboxyl group is deprotonated ( $-\text{COO}^-$ ) and the amino group is protonated ( $-\text{NH}_3^+$ ).
- There are 20 different amino acids that are used to synthesize proteins in biological systems.
  - These amino acids differ with respect to the nature of the R-group attached to their  $\alpha$ -carbon.
  - Our bodies can synthesize ten of these amino acids in quantities sufficient to meet our needs.
  - The other ten amino acids must be ingested; these are called *essential amino acids*.
- The  $\alpha$ -carbon in all amino acids, except glycine, is chiral (has four different groups attached to it).
- The two enantiomeric forms of amino acids are often called *D*- and *L*-amino acids.
  - *L*-amino acids are used to synthesize proteins in living organisms.

### Polypeptides and Proteins<sup>60,61</sup>

- Proteins are polyamides.
- When formed from amino acids, each amide group is called a **peptide bond**.
- Peptides are formed by condensation of the  $-\text{COOH}$  group of one amino acid with the  $-\text{NH}_2$  group of another amino acid.
- The acid involved in the peptide bond is named first.
  - Example: If a dipeptide is formed from alanine and glycine so that the  $-\text{COOH}$  group of glycine reacts with the  $-\text{NH}_2$  group of alanine, then the dipeptide is called *glycylalanine*.
  - Glycylalanine is abbreviated using a standard three-letter abbreviation for each amino acid, starting with the amino acid with the unreacted amino group.
    - Thus glycylalanine is abbreviated as gly-ala.
- **Polypeptides** are formed when a large number of amino acids are linked together by peptide bonds.
  - Proteins are polypeptides with molecular weights between 6000 and 50 million amu.

### Protein Structure<sup>62,63,64</sup>

- The arrangement or sequence of amino acids along a protein chain is called the protein's **primary structure** or primary sequence.
  - A change in one amino acid can alter the biochemical behavior of the protein.
    - An example of such a change is found in the disease sickle-cell anemia.
    - This disease results from a single amino acid substitution on two of the subunits of hemoglobin.
- **Secondary structure** refers to the regular arrangement of segments of the protein chain.
  - One common secondary structure is the  **$\alpha$ -helix**.
    - In an  $\alpha$ -helix, hydrogen bonds between N-H groups and carbonyl groups hold the helix in place.
    - The pitch (distance between coils) and diameter ensure that no bond angles are strained and the N-H and carbonyl functional groups are optimized for H-bonding.
  - Another common secondary structure is the  $\beta$ -pleated sheet.
- Proteins are not biologically active until they are in a particular shape.
  - The process by which the protein adopts its biologically active shape is called **folding**.

<sup>59</sup> Figure 24.18 from Transparency Pack

<sup>60</sup> "Chemistry in the Dyeing of Eggs: from Further Readings

<sup>61</sup> "Phenylalanine" 3-D Model from Instructor's Resource CD/DVD

<sup>62</sup> Figure 24.20 from Transparency Pack

<sup>63</sup> "Reversible Oxygenation of Oxygen Transport Proteins" from Further Readings

<sup>64</sup> "How Life Lost Its Symmetry" from Further Readings

- **Tertiary structure** is the three-dimensional structure of the protein.
- There are two broad categories of tertiary structure:
  - *Globular proteins*: proteins that fold into a compact, roughly spherical shape, are soluble in water and mobile in cells.
    - Globular proteins generally have nonstructural functions (e.g., enzymes).
  - *Fibrous proteins*: proteins that often feature long coils that align themselves in a fairly parallel fashion to give rise to water-insoluble fibers.
    - Fibrous proteins often play structural roles (e.g., components of hair, muscle, tendons).
- The tertiary structure is stabilized by a variety of interactions.
  - In general, polar groups on the protein tend to be found on the surface of the protein while nonpolar groups tend to be tucked away within the molecule, away from the aqueous environment.
  - The polar groups interact with solvent and other polar molecules through ion-dipole, dipole-dipole or hydrogen bonding interactions.
- Some proteins are assemblies of more than one polypeptide chain.
  - Each chain or subunit has its own tertiary structure.
  - **Quaternary structure** refers to the arrangement of the subunits.

## 24.8 Carbohydrates<sup>65,66,67,68,69,70,71</sup>

- **Carbohydrates** have the empirical formula  $C_x(H_2O)_y$ .
  - Carbohydrate means “hydrate of carbon.”
  - The most abundant carbohydrate is **glucose**,  $C_6H_{12}O_6$ .
- Carbohydrates are polyhydroxy aldehydes and ketones.
  - Glucose is a six-carbon aldehyde sugar (aldose); *fructose* is a six-carbon ketone sugar (ketose).
  - One of the alcohol groups of glucose can react with the aldehyde group to form a six-membered ring.
  - Most glucose molecules are present in the ring form.
    - Note that the six-membered rings are not planar.
  - Depending on how the ring forms, we can have one of two different isomers.
    - Consider the groups on carbons 1 and 5:
      - If the  $-CH_2OH$  group on carbon 5 and the  $-OH$  group on carbon 1 are on opposite sides of the ring, then we have the  $\alpha$  form of glucose ( $\alpha$ -anomer).
      - If they are on the same side of the ring, then we have  $\beta$  form of glucose ( $\beta$ -anomer).
  - The  $\alpha$ - and  $\beta$ - forms of glucose are very different compounds.
    - Although these differences may seem trivial, they are not.
    - For example, the difference between these two forms is the key to the difference in the structures of starch and cellulose.

<sup>65</sup> Figure 24.21 from Transparency Pack

<sup>66</sup> “An Easy Way to Convert a Fischer Projection into a Zigzag Representation” from Further Readings

<sup>67</sup> Figure 24.22 from Transparency Pack

<sup>68</sup> “The Use of Stick Figures to Visualize Fischer Projections” from Further Readings

<sup>69</sup> “Carbohydrate Stereochemistry” from Further Readings

<sup>70</sup> “A New Method to Convert the Fischer Projection of Monosaccharide to the Haworth Projection” from Further Readings

<sup>71</sup> “‘Absolutely’ Simple Stereochemistry” from Further Readings

**Disaccharides**<sup>72,73</sup>

- Glucose and fructose are **monosaccharides**, simple sugars that cannot be broken down by hydrolysis with aqueous acids.
- **Disaccharides** are sugars formed by the condensation of two monosaccharides.
  - Examples are:
    - sucrose (table sugar), which is formed by the condensation of glucose and fructose.
    - lactose (milk sugar), which is formed by the condensation of galactose and glucose.
  - Sucrose is about six times sweeter than lactose, a little sweeter than glucose, and about half as sweet as fructose.
- Disaccharides can be converted into monosaccharides by treatment with acid in aqueous solution.
  - For example, when sucrose is hydrolyzed, it gives rise to a mixture of fructose and glucose, called *invert sugar*.

**Polysaccharides**<sup>74,75,76</sup>

- **Polysaccharides** are formed by condensation of several monosaccharide units.
- There are many different types.
  - Examples of polysaccharides based on glucose are starch, glycogen, and cellulose.
- The term **starch** refers to a group of polysaccharides found in plants (e.g., corn, potatoes, wheat, rice).
  - Starch consists of many glucose units joined by linkages of the  $\alpha$  form.
  - Humans are capable of digesting starch; it is enzymatically hydrolyzed to glucose during digestion.
- **Glycogen** is a starch-like polysaccharide synthesized by muscle and liver tissues.
  - In the muscle, glycogen is an important source of quick energy.
  - In the liver, glycogen represents a storage form of glucose for the body.
    - The liver is also maintains the body's blood glucose concentration.
- **Cellulose** is a polysaccharide that is the major structural unit of plants.
  - For example, wood is approximately 50% cellulose.
  - Cellulose consists of glucose units, however, unlike starch, the glucose units present are linked in the  $\beta$  form.
    - Humans lack the enzymes required to hydrolyze cellulose.
    - Grazing animals such as cattle harbor bacteria in their digestive tract.
      - These bacteria have enzymes (cellulases) that hydrolyze cellulose.
      - The cattle are thus able to utilize the digested cellulose for food.

**24.9 Lipids**

- **Lipids** are another important class of biomolecule.
  - Lipids are used for energy storage (fats, oils) and as elements of biological structures such as cell membranes (phospholipids, cholesterol).
- Fats and oils are derived from glycerol and long-chain carboxylic acids called *fatty acids*.
  - Fats tend to be solid at room temperature and are enriched in saturated fatty acids.
    - Saturated fatty acids have R groups that are alkanes (no double bonds).
  - Oils tend to be liquid at room temperature and are enriched in unsaturated fatty acids.
    - Unsaturated fatty acids have R groups that are alkenes (at least one double bond).

<sup>72</sup> “The Biochemistry of Brewing” from Further Readings

<sup>73</sup> “Lactose” 3-D Model from Instructor’s Resource CD/DVD

<sup>74</sup> “A Variation of the Starch-Iodine Clock Reaction” from Live Demonstrations

<sup>75</sup> Figure 24.24 from Transparency Pack

<sup>76</sup> “β- and the Name with the Linkage of the Same” from Further Readings

- *Trans* fatty acids have hydrogen atoms on the opposite side of the C=C double bond.
- *Cis* fatty acids have hydrogen atoms on the same side of the C=C double bond.
- Unsaturated fatty acids may have one or more C=C double bond.
  - For example, oleic acid has one C=C double bond in the chain.
    - It is a *monounsaturated* fatty acid.
  - *Polyunsaturated* fatty acids have more than one C=C double bond in the chain.
- Some fatty acids are essential nutrients.
  - Examples include omega-3 and omega-6 fatty acids.
    - The “omega” term refers to the last carbon in the chain (the carboxylic acid carbon is the first, or alpha, one).
- Glycerol **phospholipids** also contain glycerol and fatty acid components.
  - Their structure, however, also includes a charged phosphate-containing group linked to the glycerol.
  - In an aqueous environment, phospholipids cluster together with their charged polar head groups facing the water and their nonpolar tails facing inward.
    - Thus, phospholipids form bilayers that are key components of cellular membranes.

## 24.10 Nucleic Acids<sup>77,78,79,80,81,82,83,84,85</sup>

- **Nucleic acids** carry genetic information.
  - **DNA (deoxyribonucleic acids)** have molecular weights around  $6 - 16 \times 10^6$  amu.
  - **RNA (ribonucleic acids)** have molecular weights around 20,000 to 40,000 amu.
- Nucleic acids are made up of monomers called **nucleotides**.
  - A nucleotides consist of three parts:
    - a five-carbon sugar
      - DNA and RNA have different sugars (*deoxyribose* vs. *ribose*).
    - a nitrogen-containing organic base
      - Five bases are found in DNA and RNA:
        - adenine (A),
        - guanine (G),
        - cytosine (C),
        - thymine (T found in DNA only), and
        - uracil (U found in RNA only).
    - a phosphoric acid unit
- Nucleic acids form by the condensation of nucleotides (the phosphoric acid condenses with the O–H group of the sugar).
- DNA consists of two deoxyribonucleic acid strands wound together in a **double helix**.
  - The sugar-phosphate chains are wrapped around the outside of the DNA molecule.
  - Complementary base pairs are formed between bases on each chain.
    - The complementary base pairs are held together by London-dispersion forces and hydrogen bonding.

<sup>77</sup> “Rosalind Franklin: From Coal to DNA to Plant Viruses” from Further Readings

<sup>78</sup> Figure 24.28 from Transparency Pack

<sup>79</sup> Figure 24.31 from Transparency Pack

<sup>80</sup> “DNAMonic” from Further Readings

<sup>81</sup> “A Simple Demonstration of How Intermolecular Forces Make DNA Helical” from Further Readings

<sup>82</sup> “The DNA Story” from Further Readings

<sup>83</sup> “Meeting the Matchmaker” from Further Readings

<sup>84</sup> “Glycerophospholipid (lecithin)” 3-D Model from Instructor’s Resource CD/DVD

<sup>85</sup> “Guanine” 3-D Model from Instructor’s Resource CD/DVD

- The structures of T and A make them ideal hydrogen-bonding partners.
  - Two hydrogen bonds form between T and A.
- The same is true for C and G.
  - Three hydrogen bonds form between C and G.
- During cell division, the DNA double helix unwinds.
  - Each strand serves as a template for the replication of a new strand.
  - Optimized hydrogen bonding helps to ensure that the correct bases are used along the new strand.
  - The newly synthesized DNA contains a sequence identical to that of the original molecule.
  - This allows genetic information to be preserved during cell division.

### Further Readings:

1. Raymond B. Seymour, "Alkanes: Abundant, Pervasive, Important, and Essential," *J. Chem. Educ.*, Vol. 66, **1989**, 59–63.
2. Stanislaw Skonieczny, "The IUPAC Rules for Naming Organic Molecules," *J. Chem. Educ.*, Vol. 83, **2006**, 1633–1637.
3. William B. Jensen, "Why is 'R' Used to Symbolize Hydrocarbon Substituents?," *J. Chem. Educ.*, Vol. 87, **2010**, 360–361.
4. Arnaud Haudrechy, "A Simple Method of Drawing Stereoisomers from Complicated Symmetrical Structures," *J. Chem. Educ.*, Vol. 77, **2000**, 864–866.
5. William B. Jensen, "The Origins of the Ortho-, Meta-, and Para- Prefixes in Chemical Nomenclature," *J. Chem. Educ.*, Vol. 83, **2006**, 356.
6. Michele Clarke, Ann Brown, Dianne N. Epp, Mary Gallup, Jeffrey R. Wilson, and Judith A. Wuerthele, "Ester, What's in My Food?" *J. Chem. Educ.*, Vol. 63, **1986**, 1050–1051.
7. Sophie Jourdir, "A Miracle Drug," *Chemistry in Britain*, **February 1999**, 33–35. An article about the history of aspirin.
8. Ellin Doyle, "Trans Fatty Acids," *J. Chem. Educ.*, Vol. 74, **1997**, 1030–1032.
9. Sheldon J. Kopperl, "Icie Macy Hoobler: Pioneer Woman Biochemist," *J. Chem. Educ.*, Vol. 65, **1988**, 97–98.
10. Gil Downs, "Why Teach Biochemistry?" *J. Chem. Educ.*, Vol. 64, **1987**, 339.
11. Robert C. Mebane and Thomas R. Rybolt, "Chemistry in the Dyeing of Eggs," *J. Chem. Educ.*, Vol. 64, **1987**, 291–293.
12. C. M. Drain and Barry B. Corden, "Reversible Oxygenation of Oxygen Transport Proteins," *J. Chem. Educ.*, Vol. 64, **1987**, 441–443.
13. Sandra Signorella and Luis F. Sala, "An Easy Way to Convert a Fischer Projection into a Zigzag Representation," *J. Chem. Educ.*, Vol. 68, **1991**, 105–106.
14. Jon Evans, "How Life Lost Its Symmetry," *Chemistry World*, **April 2004**, 11.
15. Laurie S. Starkey, "The Use of Stick Figures to Visualize Fischer Projections," *J. Chem. Educ.*, Vol. 78, **2001**, 1486.
16. Qing-zhi Zhang and Shen-song Zhang, "A New Method to Convert the Fischer Projection of Monosaccharide to the Haworth Projection," *J. Chem. Educ.*, Vol. 76, **1999**, 799–801.
17. Robert S. Shallenberger and Wanda J. Wienen, "Carbohydrate Stereochemistry," *J. Chem. Educ.*, Vol. 66, **1989**, 67–73.

18. Philip S. Beauchamp, “‘Absolutely’ Simple Stereochemistry,” *J. Chem. Educ.*, Vol. 61, **1984**, 666–667.
19. Charles L. Bering, “The Biochemistry of Brewing,” *J. Chem. Educ.*, Vol. 65, **1988**, 519–521.
20. James M. Garrett, “Brond the Name with the Linkage of the Same,” *J. Chem. Educ.*, Vol. 61, **1984**, 665. A mnemonic for remembering the configuration of the glucosidic linkage in disaccharides.
21. Maureen M. Julian, “Rosalind Franklin: From Coal to DNA to Plant Viruses,” *J. Chem. Educ.*, Vol. 60, **1983**, 660–662.
22. A. B. Wolbarst, “DNAmonic,” *J. Chem. Educ.*, Vol. 56, **1979**, 733. A mnemonic device for base-pairing in DNA is suggested: Pure Silver Taxi (purine: Ag; T=A, G=C).
23. Michael F. Bruist, Wayne L. Smith, and Galen Mell, “A Simple Demonstration of How Intermolecular Forces Make DNA Helical,” *J. Chem. Educ.*, Vol. 75, **1998**, 53–55.
24. Susan Aldridge, “The DNA Story,” *Chemistry in Britain*, **April 2003**, 28–30.
25. Jonathan Cox, “Meeting the Matchmaker,” *Chemistry World*, **June 2004**, 50–55. An article about DNA fingerprinting.

### Live Demonstrations:

1. Lee R. Summerlin and James L. Ealy, Jr., “Oxidation of Alcohol by  $Mn_2O_7$ ,” *Chemical Demonstrations, A Sourcebook for Teachers* (Washington: American Chemical Society, **1985**), pp. 103–104.
2. Lee. R. Summerlin,, Christie L. Borgford, and Julie B. Ealy, “The Disappearing Coffee Cup,” *Chemical Demonstrations, A Sourcebook for Teachers, Volume 2* (Washington: American Chemical Society, **1988**), p. 96. A polystyrene coffee cup is “melted” in a pool of acetone.
3. Lee. R. Summerlin,, Christie L. Borgford, and Julie B. Ealy, “Making Canned Heat,” *Chemical Demonstrations, A Sourcebook for Teachers, Volume 2* (Washington: American Chemical Society, **1988**), pp. 111–112. Saponification of stearic acid in the presence of alcohol is used to prepare a solid fuel--canned heat.
4. Claire Saxon, Scot Brindley, Nic Jervis, Graeme R. Jones, E. David Morgan, and Christopher A. Ramsden, “The World’s First ‘Pastarimeter’: An Analogous Demonstration of Polarimetry using *Pasta Fusilli*,” *J. Chem. Educ.*, Vol. 79, **2002**, 1214–1216.
5. Gretchen L. Anderson, “Demonstration of Enantiomer Specificity of Proteins and Drugs,” *J. Chem. Educ.*, Vol. 81, **2004**, 971–974. A classroom exercise to illustrate the properties of enantiomers.
6. Lee R. Summerlin, Christie L. Borgford, and Julie B. Ealy, “A Variation of the Starch-Iodine Clock Reaction,” *Chemical Demonstrations, A Sourcebook for Teachers, Volume 2* (Washington: American Chemical Society, **1987**), pp. 147–148.