Chapter 3: The Chemical Building Blocks of Life

Chapter Synopsis

Organic molecules are composed of specific functional groups that confer identity, form, and function. Many of these molecules form long-chain polymers of characteristic subunits, constituting the macromolecules upon which life depends. The bonds between subunits are formed by dehydration reactions requiring energy and resulting in the subsequent removal of one molecule of water per bond. The bonds are broken via hydrolysis reactions, releasing energy and requiring the input of water. The four types of macromolecules found within all living organisms are proteins, nucleic acids, lipids, and carbohydrates.

Proteins are a diverse group of macromolecules composed of lengthy chains of amino acid subunits. Each subunit consists of a central carbon attached to four functional groups, three that are constant among all amino acids and a fourth (the R group) that confers identity. Proteins have six levels of organization, all of which ultimately depend, therefore, on the initial amino acid sequence and the identity of each unique R group. Special proteins, chaperonins, act as molecular chaperones to help other proteins fold into their active shape. Denaturation results from changing the environmental conditions surrounding a protein. This adversely affects its biological activity, especially when it is an enzyme.

The nucleic acids, DNA and RNA, are enormously long chains of nucleotides each composed of a five-carbon sugar, a phosphate group, and one of four nitrogenous bases. Specific nucleotide identity is conferred by the base, which may be a purine or a pyrimidine. The complementarity of the nitrogenous bases allows for efficient replication of each strand and enables DNA to exist as a protected double helix. The structure of DNA and RNA differ in the sugars that constitute their backbones and in the chemical composition of one of their pyrimidine bases.

Lipids comprise the third group of macromolecules, unique in that they are completely insoluble in water. The simplest are the fats, which provide ideal long-term energy reserves due to their numerous C—H bonds. Other lipids are important components of biological membranes and have polar ends that orient towards water and nonpolar tails that orient away from it. Carbohydrates include the monosaccharides, single subunits that serve as energy storage molecules, the two unit disaccharides that are plant transport molecules, and the polysaccharides, molecules hundreds of glucose units long and insoluble as a result of their coils or branches. Cellulose and chitin are important structural carbohydrates because most organisms lack the means to degrade them.

Chapter Objectives

- ä Identify the four macromolecules. Know their basic chemical compositions and how each is important to living organisms.
- ä Know how various molecular subunits polymerize to form chains of organic macromolecules.
- ä Understand the consequences of dehydration and hydrolysis reactions and how they are dependent upon water.
- ä Know the importance of an amino acid R group.
- ä Describe the six levels of protein structure and the forces that help maintain each level.
- ä Understand how chaperonins are involved in protein folding and unfolding.
- ä Understand the difference between a helix and a double helix in DNA and RNA.
- ä Compare DNA and RNA in terms of chemical composition and basic cellular function.

ä Differentiate between saturated and unsaturated fats, in the types of bonds they possess, their relative amounts of hydrogen, their energy content, and their consistency at room temperature.

ä Know how and why monosaccharides combine to form the various common disaccharides and polysaccharides.

ä Compare cellulose and chitin to one another and to other polysaccharides in terms of their chemical composition and their digestibility.

ä Contrast lipids and starches with respect to their solubility in water and their efficiency in storing chemical energy.

KEY TERMS

alpha form
amino acid
beta form
carbohydrate
chaperonin
complementary
contractile protein
dehydration synthesis
deoxyribonucleic acid (DNA)
denaturation
disaccharide
dissociation
domain
double helix
fat
functional group
hydrocarbon
hydrolysis
isomer
intercellular messenger
levo- sugar
macromolecule
monosaccharide
nucleic acid
nucleotide
organic molecule
peptide bond
polypeptide
polysaccharide
polyunsaturated fatty acid
protein
ribonucleic acid (RNA)
saturated fatty acid
starch
structural polysaccharide
triacylglycerol (triglyceride)
unsaturated fatty acid

CHAPTER OUTLINE

3.0 Introduction

I. MOLECULES ARE IMPORTANT TO BIOLOGY

A. Many Molecules Are Very Small

B. Other Molecules Are Very Large fig 3.1
1. Called macromolecules
2. Four general types

3.1 Molecules are the building blocks of life

I. THE CHEMISTRY OF CARBON

A. Organic Molecules Contain Carbon
1. Four electrons needed to fill outer orbital
   a. Has four equidistant binding sites
   b. Forms single, double, and triple bonds with itself

2. Chains are linked together in a biological framework
   a. Forms straight or branched chains or closed rings
   b. Hydrogen, oxygen, nitrogen, or other atoms added to chains
3. Hydrocarbons are constructed of only carbon and hydrogen
   a. Example: Propane
   b. Make good fuels

B. Functional Groups
  1. Similar electronegativities between carbon and hydrogen
    a. Electrons in bonds evenly distributed
    b. No difference in charge over molecule surface
  2. Atoms with different electronegativities confer regions of charge
    a. May be positive or negative
    b. Molecules are then polar
  3. Functional groups of elements attach to carbon framework
    a. Example: Hydroxyl group is ^{-}OH — fig 3.2
    b. Have definite chemical properties
    c. Most chemical reactions involve transfer of these groups

C. Biological Macromolecules
  1. Large complex assemblies
    a. Structural or informational function
    b. Many are polymers, repeating units bonded together
  2. Four classes: Carbohydrates, lipids, proteins, nucleic acids — tbl 3.1

D. Building Macromolecules
  1. Dehydration synthesis (reaction) — fig 3.3a
    a. Molecule of water removed as subunits are linked
    b. Requires input of energy to assemble
    c. Catalysis carried out by enzymes
  2. Hydrolysis reaction — fig 3.3b
    a. Molecule of water added as subunits are broken apart
    b. Reactions disassemble molecules to subunits, energy released

3.2 Proteins perform the chemistry of the cell

I. THE MANY FUNCTIONS OF PROTEINS — tbl 3.1

A. Diverse Functions — tbl 3.2, fig 3.4
  1. Enzyme catalysis
    a. Facilitate biological reactions
    b. Globular, three-dimensional shape
  2. Defense
    a. Also globular in shape, recognize foreign cells
    b. Include cell surface receptors
  3. Transport
    a. Globular proteins that transport small molecules and ions
    b. Examples: Hemoglobin, myoglobin, transferrin
  4. Support — fig 3.4
    a. Fibrous proteins are structural
    b. Include keratin, fibrin, collagen
    c. Most abundant protein in vertebrates
  5. Motion
    a. Muscle contraction due to sliding of actin and myosin filaments
    b. Contractile proteins in cytoskeleton within cell
  6. Regulation
    a. Hormones are intercellular messengers
    b. Cell surface receptors receive information

II. AMINO ACIDS ARE THE BUILDING BLOCKS OF PROTEIN

A. Complex, Versatile Molecules
   1. Polymers of only 20 amino acids
   2. Among first biological molecules to evolve

B. Amino Acid Structure
   1. Amino, carboxyl, hydrogen bonded to central carbon
   2. Identity conferred by variable R group
   3. Five classes
      a. Nonpolar
         1) Example: Leucine
         2) Often contain —CH_2 or —CH_3
      b. Polar, uncharged
         1) Example: Threonine
         2) Contain oxygen or only —H
      c. Ionizable
         1) Example: Glutamic acid
         2) Contain acids or bases
      d. Aromatic
         1) Example: Phenylalanine
         2) Contain organic ring with alternating single and double bonds
      e. Special function
         1) Examples: Methionine, proline, cysteine
         2) Confer unique individual properties
   4. Affects shape of protein depending on its chemical properties

C. Proteins Are Polymers of Amino Acids
   1. Ionized amino acid has amino (NH_3^+) on one end, carboxyl(COO^-) on other
   2. Amino acids are linked together by peptide bonds fig 3.5
      a. Condensation reaction between amino and carboxyl ends
      b. Lose water molecule, form covalent bond
      c. Bond is stiff, molecules cannot rotate
   3. Proteins composed of one or more polypeptides
   4. Polypeptides are long chains of amino acids
   5. Each protein has a unique, defined amino acid sequence
   6. 20 common amino acids with characteristic side groups fig 3.6

III. A PROTEIN'S FUNCTION DEPENDS ON THE SHAPE OF THE MOLECULE

A. Overview of Protein Structure
   1. Proteins are amino acid chains folded up into complex shapes
   2. Examine three dimensional structure with X-ray diffraction
      a. Myoglobin was first one examined
      b. All internal amino acids are nonpolar
      c. Hydrophobic interactions shove nonpolar molecules inside
      d. Polar and charged amino acids usually on surface of protein

B. Levels of Protein Structure
   1. Possess structural levels fig 3.7
      a. Four initial levels: Primary, secondary, tertiary, and quaternary structures
      b. Two additional levels: Motifs and domains

2. Primary structure
   a. Specific amino acid sequence determined by gene's nucleotide sequence
   b. Permits great diversity of proteins
3. Secondary structure
   a. Side groups, —COOH and —NH groups of main chain form hydrogen bonds
   b. Two patterns of H bonding
      1) Linking of two amino acids along chain forms α (alpha) helix
      2) Many parallel links across two chains forms β (beta) pleated sheet
4. Motifs
   a. Sometimes called supersecondary structure
   b. β α β (beta-alpha-beta) creates fold or crease
   c. "Rossman fold" is an α β α β α β motif
   d. β-barrel is a β sheet folded into a tube
   e. α-turn-α binds to DNA double helix
5. Tertiary structure
   a. Protein's final folded shape, positions motifs and side groups
   b. Spontaneous, driven by hydrophobic interactions with water
   c. Nonpolar chains in close proximity exhibit van der Waal's forces
   d. Allow very close fitting of nonpolar chains in protein interior
   e. Single amino acid change can significantly disrupt fit
6. Domains
   a. Exon-encoded, structurally independent globular unit
      1) Sections are 100 to 200 amino acids long
      2) Fold into shape independently
      3) Forms same shape alone or within whole protein
   b. Domains connected to each other by single polypeptide chain
   c. Each domain may have different function
7. Quaternary structure
   a. Combination of two or more polypeptide subunits
   b. Composes functional unit of a protein
   c. Change in one amino acid can have profound effect – sickle cell anemia

IV. HOW PROTEINS FOLD INTO THEIR FUNCTIONAL SHAPE

A. Nonpolar Proteins Play Key Role in Protein Folding
   1. Folding not simple hydrophobic interaction
   2. Sticky interior portions exposed during intermediate stages

B. Chaperonins
   1. Special proteins that help new proteins fold correctly — fig 3.8
      a. Identified in *E.coli* bacteria
      b. If disabled, 30% of proteins fail to fold properly
   2. More than 17 kinds of proteins act as molecular chaperones
      a. Include heat shock proteins
      b. High temperatures cause protein to unfold, heat shock chaperonins help refold
   3. Controversy regarding how chaperonins work
      a. First thought to provide protected environment
      b. Now thought that they rescue proteins in wrongly folded state

C. Protein Folding and Disease
   1. Cystic fibrosis membrane transport protein
      a. Protein moves ions across cell membranes
      b. Sometimes amino acid sequence is correct, protein fails to fold
   2. May cause Alzheimer's disease with protein clumping in brain tissue

V. HOW PROTEINS UNFOLD

A. Denaturation
1. Protein shape altered with changes in pH, temperature, ion concentration
2. Protein becomes biologically inactive
3. Enzymes function only within a narrow environmental range

B. Small Proteins May Return to Natural Shape fig 3.9
1. Large proteins rarely refold naturally
2. Distinguish denaturation from dissociation fig 3.10
a. Subunits may dissociate without denaturing folded proteins
b. Can readily reassume subunit quaternary structure

3.3 Nucleic acids store and transfer the genetic information

I. INFORMATION MOLECULES tbl 3.1

A. Cellular Information Storage Devices
1. Cell biochemistry dependent on proteins with specific sequence
a. Ability to produce correct proteins is passed between generations
b. Proteins not passed from generation to generation
2. Two forms of hereditary material
a. Deoxyribonucleic acid = DNA, master molecule fig 3.11
b. Ribonucleic acid = RNA, template copy

B. "Seeing" DNA
1. To small to be resolved by optical or electron microscopes
2. Visualized using scanning-tunneling microscope fig 3.12
3. Other microscopes work by bouncing light or electrons off object
4. Scanning-tunneling microscope place a probe on surface
a. Like feeling object with a hand
b. Probe advances in steps smaller than diameter of an atom

C. The Structure of Nucleic Acids
1. Chemical components fig 3.13
a. Five-carbon ribose or deoxyribose sugar
b. Phosphate group
c. Organic nitrogen-containing base
2. Phosphodiester bonds join sugars
3. Nitrogen base attached to sugar and protrudes from chain
4. Two kinds of organic bases fig 3.14
a. Purines: Adenine (A), guanine (G)
b. Pyrimidines: Cytosine (C), thymine (T) (in DNA), uracil (U) (in RNA)

D. DNA
1. Sequential nucleotides store hereditary information
2. DNA forms double chains fig 3.15
a. Helix is a spiral staircase shape
b. Two intertwined DNA molecules form a double helix
c. Hydrogen bonds between bases hold chains together as duplex
3. Base pairing is specific and complementary
a. Adenine with thymine (in DNA) or uracil (in RNA)
b. Guanine with cytosine (in DNA and RNA)

E. RNA
1. Chemical differences between RNA and DNA
a. RNA contains ribose sugar with hydroxyl at carbons 2 and 3
b. Uracil base in RNA, thymine in DNA
2. Single stranded helix under most circumstances fig 3.16

F. Which Came First, DNA or RNA
1. DNA stores information for protein synthesis
a. RNA is the working copy of DNA master information
b. DNA protected by not being actively used to make protein
2. DNA evolved from RNA to protect the genetic information
3. Flow of genetic information: DNA → RNA → protein

G. ATP fig 3.17
1. Adenosine triphosphate = ATP
2. Nicotinamide adenine dinucleotide = NAD^+
3. Flavin adenine dinucleotide = FAD^+

3.4 Lipids make membranes and store energy

I. FATS AND OILS

A. Lipids Are Insoluble in Water tbl 3.1
1. Ratio of H to O is higher than carbohydrates
2. Are lipids that are insoluble due to nonpolar nature
a. Cannot form hydrogen bonds like water can
b. Lipid molecules cluster together and exclude water
1) Polar groups exposed to water
2) Nonpolar parts sequestered together inside of cluster
3. Assembly is spontaneous

II. PHOSPHOLIPIDS FORM MEMBRANES

A. Structure of Phospholipids
1. Phospholipids composed of three subunit molecules
a. Glycerol
1) A three carbon alcohol, each carbon has a hydroxyl group
2) Forms backbone of molecule
b. Fatty acids
1) Long chains of C—H bonds
2) Two attached to each phospholipid molecule
c. Phosphate group
1) Attaches to one end of glycerol
2) Charged unit usually has charged organic molecule linked to it
2. Molecule has polar head and two nonpolar tails
a. Head is the phosphate group
b. Tails are fatty acid chains, aggregate away from water
3. Form lipid bilayer fig 3.18
a. Two layers of tails point inward at each other
b. Basic framework of biological membranes

III. FATS AND OTHER KINDS OF LIPIDS

A. Fats Are Triglycerides

1. Lack polar ends, contains three fatty acids — fig 3.19
    a. Also called a triacylglycerol
    b. Three fatty acids may not be identical
    c. Provide energy storage in many C—H bonds
2. Are not soluble in water
    a. Spontaneously form clumps of fat globules when placed in water
    b. Can be deposited as storage fats at specific locations in organisms
3. Many other types of lipids exist — tbl 3.1
    a. Oils: Include olive, corn, and coconut oils
    b. Waxes: Include beeswax and earwax
4. Saturated fatty acids — fig 3.20
    a. Internal carbons bonded to at least 2 hydrogens
    b. Single bonds between carbons, possess maximum number of hydrogen atoms
    c. Are solid at room temperature, like butter
5. Unsaturated fatty acids
    a. Internal carbons have fewer hydrogens
    b. Double bonds between many carbons
    c. Polyunsaturated fats have more than one double bond
    d. Have low melting points
        1) Fatty acid chains bend at double bonds
        2) Molecules cannot align closely with each other
    e. Are usually liquid at room temperature like corn oil

B. Other Kinds of Lipids — fig 3.19

1. Terpenes
    a. Form various long-chain pigments
    b. Examples: Chlorophyll, retinal, rubber
2. Steroids
    a. Also found in membranes
    b. Composed of four carbon rings
    c. Cell membranes often contain cholesterol
    d. Testosterone and estrogen are hormones in multicellular animals
3. Prostaglandins
    a. Are modified fatty acids
    b. Composed of two nonpolar tails attached to ring
    c. Variety of biological functions, local chemical messengers

IV. FATS AS FOOD

A. Fats Are Efficient Energy Storage Molecules

1. Contain many C—H bonds
    a. Many more than carbohydrates
    b. Yield 9 kcal per gram fat, 4 kcal per gram carbohydrate
2. Animal fats are generally saturated, plants are unsaturated
    a. Some fish oils are unsaturated
    b. Oils can be artificially hydrogenated to produce solid fats
    c. Natural unsaturated fats are healthier than highly hydrogenated fats
    d. Both saturated fats and artificially hydrogenated fats are unhealthy
3. Conversion of excess consumed carbon molecules
    a. Converted into starch, glycogen, fat to be used in future
    b. Related to weight gain with age

B. High Fat Diet Is Unhealthy
   1. Contributes to heart disease, atherosclerosis
   2. Plaque fragments cause strokes

3.5 Carbohydrates store energy and provide building materials

I. SIMPLE CARBOHYDRATES

A. A Variety of Forms
   1. Some function in energy storage, others are structural
   2. Some are small and simple, others are long polymers

B. Sugars Are Simple Carbohydrates
   1. Contain C, H, O in 1:2:1 ratio
      a. C—H bonds release energy when broken
      b. Well-suited for storage function
   2. Monosaccharides
      a. Contain as few as three carbon atoms — fig 3.21
      b. Empirical formula $C_6H_{12}O_6$ or $(CH_2O)_6$
      c. May exist in straight chains that form rings in solution in water
      d. Primary six carbon sugar is glucose — fig 3.22
   3. Disaccharides
      a. Double sugars include sucrose — fig 3.23
      b. Composed of two monosaccharides joined by a covalent bond
      c. Important in transport of sugars
   4. Polysaccharides
      a. Macromolecules composed of monosaccharide subunits
      b. Starch is used by plants to store energy
      c. Cellulose is a plant structural molecule, special enzymes needed to break links

C. Sugar Isomers
   1. Have same empirical formula — fig 3.24
   2. Atoms are arranged differently
      a. Glucose and fructose are structural isomers
      b. Glucose and galactose are stereoisomers

II. LINKING SUGARS TOGETHER

A. Transport Disaccharides — fig 3.25a
   1. Protects sugar from being metabolized during transport
   2. Are made of two monosaccharides linked together
   3. Enzymes that break this bond are only present in glucose-using tissue
   4. Types of transport disaccharides
      a. Sucrose = glucose + fructose
      b. Lactose = glucose + galactose

B. Storage Polysaccharides — fig 3.25b
   1. Metabolic energy stored as disaccharide maltose (glucose + glucose)
   2. Maltose units linked to form insoluble forms
   3. Insoluble polymers called polysaccharides
   4. Starches are polysaccharides made from glucose
   5. Amylose is the simplest form in plants
      a. Carbon 1 of glucose bonds to carbon 4 of next glucose
      b. Chains of maltose that coil in water — fig 3.26a

6. Pectins are branched polysaccharides in plants
   a. Called amylopectin when based on amylose — fig 3.26b
   b. Branches formed by cross-links, short chain length between branches
   c. Results in meshwork of linked glucose units
7. Glycogen is branched form in animals
   a. Insoluble polysaccharide with long chain length
   b. Great number of branches — fig 3.26c

C. Nonfattening Sweets
1. Most sugars are "right-handed," hydroxyl is on right side
2. "Left-handed" sugars can be made artificially
   a. Cannot be broken down by enzymes for right-handed sugars
   b. Called levo- or l-sugars
   c. Not digested by body, cannot contribute to tooth decay

III. STRUCTURAL CARBOHYDRATES

A. Cellulose
1. Orientation of glucose subunits
   a. In starch the units are all alpha form of glucose
   b. In cellulose the units are beta form of glucose
2. Structural polysaccharide is component of plant cell walls — fig 3.27
   a. Chemically similar to amylose
   b. Different bonds connect subunits
   c. Cannot be degraded by enzyme that breaks amylose beta-glucose bonds
   d. Undigestible by most organisms, human dietary fiber
   e. Degraded by certain bacteria and protists

B. Chitin
1. Structural modification produces chitin — fig 3.28
   a. Present in insects and fungi
   b. Adds nitrogen group to glucose units
2. Few organisms can digest this compound

INSTRUCTIONAL STRATEGY

PRESENTATION ASSISTANCE:

The content of this chapter builds upon that of the previous one. The emphasis here is chemistry as it relates to the composition of living organisms. This material is a necessary "evil" to understand most of the remainder of this text, including cellular organization, physiology, energetics, heredity, and (with current molecular trends) even organismal taxonomy. Unfortunately, chemistry is one of the reasons your students may have enrolled in biology, assuming it to be less rigorous than chemistry or physics.

Do not assume that your students will inherently understand what you mean when you draw C—H or C = O on the overhead or blackboard. Explain the conventions of biochemistry and define any abbreviations you find useful, including CHO for carbohydrates, AA for amino acids, FA for fatty acids. This is valuable not only from an informational standpoint, but it will improve their note-taking in class. Mnemonics, acronyms, and various word associations may also be helpful to the beginning student. It is easy to remember which molecules are pyrimidines and which are purines if one associates the smaller molecule with the larger name.

It is important that your students completely understand the structure of a five carbon sugar molecule. The apex of the pentagon is an oxygen molecule, the four other corners are carbons. The number 4 carbon has the number 5 carbon attached to it. Students may mistakenly interpret the simpler drawings of the phosphodiester bond as having the phosphate attached to the number 4 carbon instead of the number 5 carbon. This will be more important in chapters 13 and 14 when the synthesis of DNA is presented and students must understand what is meant by the 3′ and 5′ ends of the molecule.

The hydroxyl placement on the DNA and RNA sugar molecules has a strong bearing on the stability of the linear molecule. RNA has hydroxyls on both the 2 and 3 carbons, therefore the phosphodiester bond can jump between them. DNA has a hydroxyl on only the number 3 carbon, the phosphate can attach only at that location.

VISUAL RESOURCES:

Use molecular models whenever possible, make sure they are large enough to be seen in the back row. Construct your own from ping pong balls and pencils, or styrofoam balls and straws. Pop-it beads are valuable for describing polymerization of nearly all of the biomolecules, especially amino acids forming polypeptide chains. A coiled telephone cord effectively resembles an alpha helix.

Several supply companies sell plastic biomolecule sets made of clinging plastic that are of sufficient size for small to medium size classes. One could construct similar sets from differently shaped or colored acetate pieces for use on an overhead in a very large class setting.