CHAPTER 5
THE STRUCTURE AND FUNCTION
OF MACROMOLECULES

OUTLINE

  I.   Polymer Principles
      A. Most macromolecules are polymers
      B. A limitless variety of polymers can be built from a small set of monomers
  II.   Carbohydrates: Fuel and Building Material
      A. Sugars, the smallest carbohydrates, serve as fuel and carbon sources
      B. Polysaccharides, the polymers of sugars, have storage and structural roles
  III. Lipids: Diverse Hydrophobic Molecules
      A. Fats store large amounts of energy
      B. Phospholipids are major components of cell membranes
      C. Steroids include cholesterol and certain hormones
  IV. Proteins: The Molecular Tools of the Cell
      A. A polypeptide is a polymer of amino acids connected in a specific sequence
      B. A protein's function depends on its specific conformation
  V.   Nucleic Acids: Informational Polymers
      A. Nucleic acids store and transmit hereditary information
      B. A nucleic acid strand is a polymer of nucleotides
      C. Inheritance is based on replication of the DNA double helix
      D. We can use DNA and proteins as tape measures of evolution

OBJECTIVES

After reading this chapter and attending lecture, the student should be able to:

1.   List the four major classes of biomolecules.
2.   Explain how organic polymers contribute to biological diversity.
3.   Describe how covalent linkages are formed and broken in organic polymers.
4.   Describe the distinguishing characteristics of carbohydrates, and explain how they are classified.
5.   List four characteristics of a sugar.
6.   Identify a glycosidic linkage and describe how it is formed.
7.   Describe the important biological functions of polysaccharides.
8.   Distinguish between the glycosidic linkages found in starch and cellulose, and explain why the difference is biologically important.
9.   Explain what distinguishes lipids from other major classes of macromolecules.
10.   Describe the unique properties, building block molecules and biological importance of the three important groups of lipids: fats, phospholipids and steroids.

11. Identify an ester linkage and describe how it is formed.
12. Distinguish between a saturated and unsaturated fat, and list some unique emergent properties that are a consequence of these structural differences.
13. Describe the characteristics that distinguish proteins from the other major classes of macromolecules, and explain the biologically important functions of this group.
14. List and recognize four major components of an amino acid, and explain how amino acids may be grouped according to the physical and chemical properties of the side chains.
15. Identify a peptide bond and explain how it is formed.
16. Explain what determines protein conformation and why it is important.
17. Define primary structure and describe how it may be deduced in the laboratory.
18. Describe the two types of secondary protein structure, and explain the role of hydrogen bonds in maintaining the structure.
19. Explain how weak interactions and disulfide bridges contribute to tertiary protein structure.
20. Using collagen and hemoglobin as examples, describe quaternary protein structure.
21. Define denaturation and explain how proteins may be denatured.
22. Describe the characteristics that distinguish nucleic acids from the other major groups of macromolecules.
23. Summarize the functions of nucleic acids.
24. List the major components of a nucleotide, and describe how these monomers are linked together to form a nucleic acid.
25. Distinguish between a pyrimidine and a purine.
26. List the functions of nucleotides.
27. Briefly describe the three-dimensional structure of DNA.

KEY TERMS

polymer	cellulose	polypeptide	quaternary structure
monomer	chitin	amino acid	denaturation
condensation reaction	lipid	protein	chaperone proteins
dehydration reaction	fat	conformation	gene
hydrolysis	fatty acid	peptide bond	nucleic acid
carbohydrate	triacylglycerol	primary structure	deoxyribonucleic acid
monosaccharide	saturated fatty acid	secondary structure	ribonucleic acid
disaccharide	unsaturated fatty acid	alpha (α) helix	nucleotide
glycosidic linkage	steroid	pleated sheet	pyrimidine
polysaccharide	cholesterol	tertiary structure	purine
starch	protein	hydrophobic interaction	ribose
glycogen	conformation	disulfide bridges	polynucleotide
double helix			

LECTURE NOTES

The topic of macromolecules lends itself well to illustrate three integral themes that permeate the text and course:

1. There is a natural hierarchy of structural level in biological organization.
2. As one moves up the hierarchy, new properties emerge because of interactions among subunits at the lower levels.
3. Form fits function.

I.   Polymer Principles

A. Most macromolecules are polymers

Polymer = (Poly = many; mer = part); large molecule consisting of many identical or similar subunits connected together.

Monomer = Subunit or building block molecule of a polymer

Macromolecule = (Macro = large); large organic polymer

- Formation of macromolecules from smaller building block molecules represents another level in the hierarchy of biological organization.

- There are four classes of macromolecules in living organisms:

  1. Carbohydrates

  2. Lipids

  3. Proteins

  4. Nucleic acids

Most polymerization reactions in living organisms are condensation reactions.

- *Polymerization reactions* = Chemical reactions that link two or more small molecules to form larger molecules with repeating structural units.

- *Condensation reactions* = Polymerization reactions during which monomers are covalently linked, producing net removal of a water molecule for each covalent linkage.

  - One monomer loses a hydroxyl (–OH), and the other monomer loses a hydrogen (–H).

  - Removal of water is actually indirect, involving the formation of "activated" monomers (discussed in Chapter 6, Introduction to Metabolism).

  - Process requires energy.

  - Process requires biological catalysts or enzymes.

Hydrolysis = (Hydro = water; lysis = break); a reaction process that breaks covalent bonds between monomers by the addition of water molecules.

- A hydrogen from the water bonds to one monomer, and the hydroxyl bonds to the adjacent monomer.

- Example: Digestive enzymes catalyze hydrolytic reactions which break apart large food molecules into monomers that can be absorbed into the bloodstream.

B. An immense variety of polymers can be built from a small set of monomers

Structural variation of macromolecules is the basis for the enormous diversity of life.

- There is *unity* in life as there are only about 40 to 50 common monomers used to construct macromolecules.

- There is *diversity* in life as new properties emerge when these universal monomers are arranged in different ways.

II.   Carbohydrates: Fuel and Building Material

A. Sugars, the smallest carbohydrates, serve as fuel and carbon sources

Carbohydrates = Organic molecules made of sugars and their polymers

- Monomers or building block molecules are simple sugars called *monosaccharides*.

- Polymers are formed by condensation reactions.

- Carbohydrates are classified by the number of simple sugars.

1. Monosaccharides

Monosaccharides = (Mono = single; sacchar = sugar); simple sugar in which C, H, and O occur in the ratio of (CH_2O).
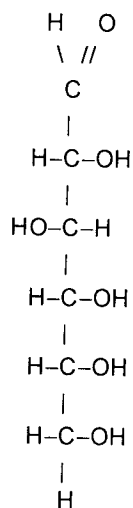
- Are major nutrients for cells; glucose is the most common
- Can be produced (glucose) by photosynthetic organisms from CO_2, H_2O, and sunlight
- Store energy in their chemical bonds which is harvested by cellular respiration
- Their carbon skeletons are raw material for other organic molecules.
- Can be incorporated as monomers into disaccharides and polysaccharides

Characteristics of a sugar:

a. An –OH group is attached to each carbon except one, which is double bonded to an oxygen (*carbonyl*).

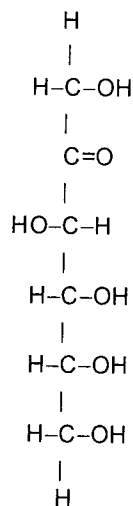| **Aldehyde**	**Ketone**
Terminal carbon forms a double bond with oxygen.	Carbonyl group is within the carbon skeleton.

```
        H   O                         H
         \  //                        |
          C                         H-C-OH
          |                           |
        H-C-OH                       C=O
          |                           |
        HO-C-H                      HO-C-H
          |                           |
        H-C-OH                       H-C-OH
          |                           |
        H-C-OH                       H-C-OH
          |                           |
        H-C-OH                       H-C-OH
          |                           |
          H                           H
       Glucose                     Fructose
       (aldose)                    (ketose)
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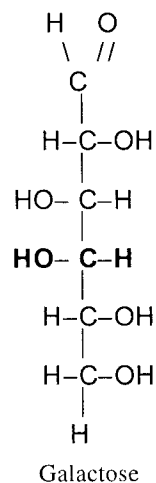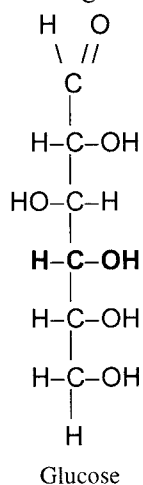
b. Size of the carbon skeleton varies from three to seven carbons. The *most common* monosaccharides are:

Classification	Number of Carbons	Example
Triose	3	Glyceraldehyde
Pentose	5	Ribose
Hexose	6	Glucose

c. Spatial arrangement around asymmetric carbons may vary. For example, glucose and galactose are enantiomers.

Glucose   Galactose

The small difference between isomers affects molecular shape which gives these molecules distinctive biochemical properties.

d. In aqueous solutions, many monosaccharides form rings. Chemical equilibrium favors the ring structure.

Linear Form   Ring Form of Glucose
of Glucose
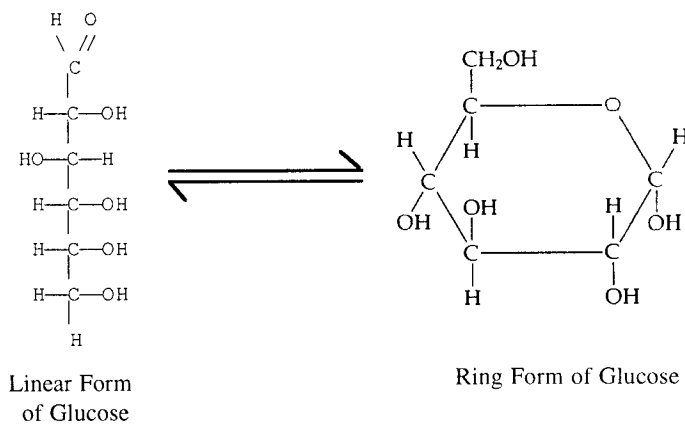
2. Disaccharides

Disaccharide = (Di = two; sacchar = sugar); a double sugar that consists of two monosaccharides joined by a *glycosidic linkage*.

Glycosidic linkage = Covalent bond formed by a condensation reaction between two sugar monomers; for example, maltose:
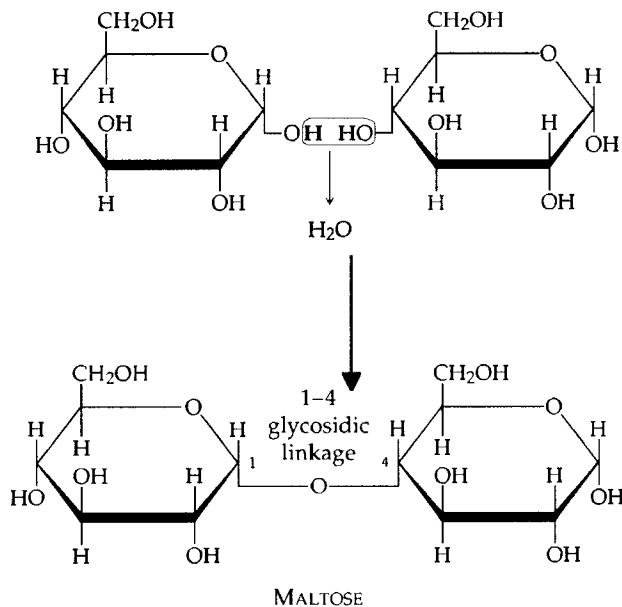
MALTOSE

Examples of disaccharides include:

Disaccharide	Monomers	General Comments
Maltose	Glucose + Glucose	Important in brewing beer
Lactose	Glucose + Galactose	Present in milk
Sucrose	Glucose + Fructose	Table sugar; most prevalent disaccharide; transport form in plants

B. Polysaccharides, the polymers of sugars, have storage and structural roles

Polysaccharides = Macromolecules that are polymers of a few hundred or thousand monosaccharides.

- Are formed by linking monomers in enzyme-mediated condensation reactions
- Have two important biological functions:
  1. Energy storage (starch and glycogen)
  2. Structural support (cellulose and chitin)

1. Storage polysaccharides

Cells hydrolyze storage polysaccharides into sugars as needed. Two most common storage polysaccharides are *starch* and *glycogen*.

Starch = Glucose polymer that is a storage polysaccharide in plants.

- Helical glucose polymer with α 1-4 linkages (see Campbell, Figure 5.6)
- Stored as granules within plant organelles called *plastids*
- *Amylose*, the simplest form, is an unbranched polymer.
- *Amylopectin* is branched polymer.
- Most animals have digestive enzymes to hydrolyze starch.
- Major sources in the human diet are potato tubers and grains (e.g., wheat, corn, rice, and fruits of other grasses).

Glycogen = Glucose polymer that is a storage polysaccharide in animals.
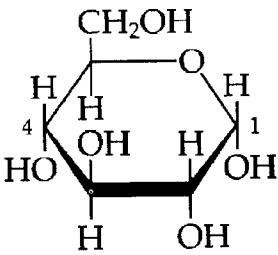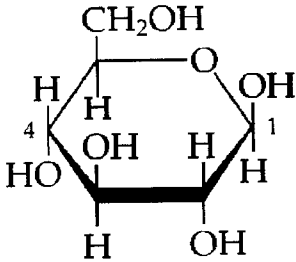
- Large glucose polymer that is more highly branched (α 1-4 and 4-6 linkages) than amylopectin
- Stored in the muscle and liver of humans and other vertebrates

2. Structural polysaccharides

Structural polysaccharides include *cellulose* and *chitin*.

Cellulose = Linear unbranched polymer of *D*-glucose in (α 1-4, β 4-6) linkages.

- A major structural component of plant cell walls
- Differs from starch (also a glucose polymer) in its glycosidic linkages (see Campbell, Figure 5.7)

STARCH	CELLULOSE
Glucose monomers are in α *configuration* (–OH group on carbon one is *below* the ring's plane).	Glucose monomers are in β *configuration* (–OH group on carbon one is *above* the ring's plane).
Monomers are connected with α 1-4 linkage.	Monomers are connected with β 1-4 linkage.

- Cellulose and starch have different three-dimensional shapes and properties as a result of differences in glycosidic linkages.
- Cellulose reinforces plant cell walls. Hydrogen bonds hold together parallel cellulose molecules in bundles of *microfibrils* (see Campbell, Figure 5.8)
- Cellulose cannot be digested by most organisms, including humans, because they lack an enzyme that can hydrolyze the β 1-4 linkage. (Exceptions are some symbiotic bacteria, other microorganisms and some fungi.)

Chitin = A structural polysaccharide that is a polymer of an amino sugar (see Campbell, Figure 5.9).

- Forms exoskeletons of arthropods
- Found as a building material in the cell walls of some fungi
- Monomer is an *amino sugar*, which is similar to *beta*-glucose with a nitrogen-containing group replacing the hydroxyl on carbon 2.
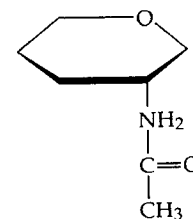
III.   Lipids: Diverse Hydrophobic Molecules

Lipids = Diverse group of organic compounds that are insoluble in water, but will dissolve in nonpolar solvents (e.g., ether, chloroform, benzene). Important groups are *fats*, *phospholipids*, and *steroids*.

A.   Fats store large amounts of energy

Fats = Macromolecules are constructed from (see Campbell, Figure 5.10):

1. Glycerol, a three-carbon alcohol
2. Fatty acid (carboxylic acid)
   - Composed of a carboxyl group at one end and an attached *hydrocarbon chain* ("tail")
   - Carboxyl functional group ("head") has properties of an acid.
   - Hydrocarbon chain has a long carbon skeleton usually with an even number of carbon atoms (most have 16 – 18 carbons).
   - Nonpolar C–H bonds make the chain hydrophobic and not water soluble.

During the formation of a fat, enzyme-catalyzed condensation reactions link glycerol to fatty acids by an ester linkage.

Ester linkage = Bond formed between a hydroxyl group and a carboxyl group.

Each of glycerol's three hydroxyl groups can bond to a fatty acid by an ester linkage producing a fat.

Triacylglycerol = A fat composed of three fatty acids bonded to one glycerol by ester linkages (triglyceride).
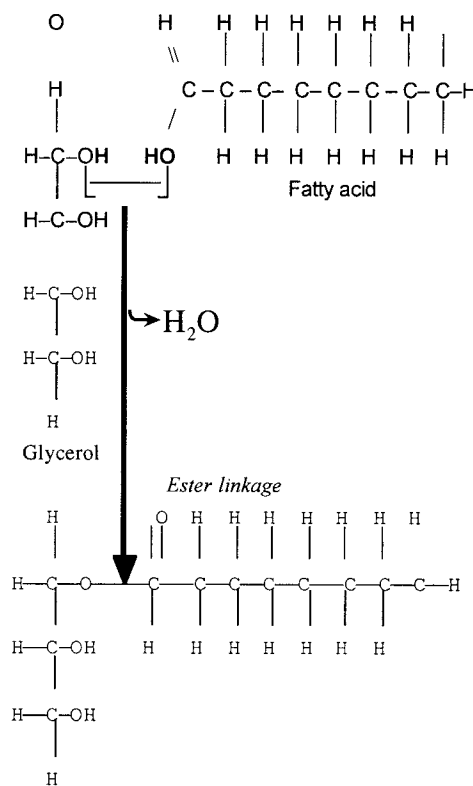
Some characteristics of fat include:

- Fats are insoluble in water. The long fatty acid chains are hydrophobic because of the many nonpolar C–H bonds.
- The source of variation among fat molecules is the fatty acid composition.
- Fatty acids in a fat may all be the same, or some (or all) may differ.
- Fatty acids may vary in length.
- Fatty acids may vary in the number and location of carbon-to-carbon double bonds.

SATURATED FAT	UNSATURATED FAT
No double bonds between carbons in fatty acid tail	One or more double bonds between carbons in fatty acid tail
Carbon skeleton of fatty acid is bonded to maximum number of hydrogens (*saturated* with hydrogens)	Tail kinks at each C=C, so molecules do not pack closely enough to solidify at room temperature
Usually a solid at room temperature	Usually a liquid at room temperature
Most animal fats	Most plant fats
e.g., bacon grease, lard and butter (see Campbell, Figure 5.11)	e.g., corn, peanut and olive oil

- In many commercially prepared food products, unsaturated fats are artificially hydrogenated to prevent them from separating out as oil (e.g., peanut butter and margarine).

Fat serves many useful functions:

- Energy storage. One gram of fat stores twice as much energy as a gram of polysaccharide. (Fat has a higher proportion of energy rich C–H bonds.)
- More compact fuel reservoir than carbohydrate. Animals store more energy with less weight than plants which use starch, a bulky form of energy storage.
- Cushions vital organs in mammals (e.g., kidney).
- Insulates against heat loss (e.g., in mammals such as whales and seals).

B. Phospholipids

Phospholipids = Compounds with molecular building blocks of glycerol, two fatty acids, a phosphate group, and usually, an additional small chemical group attached to the phosphate (see Campbell , Figure 5.12)

- Differ from fat in that the third carbon of glycerol is joined to a *negatively charged* phosphate group
- Can have small variable molecules (usually charged or polar) attached to phosphate
- Are diverse depending upon differences in fatty acids and in phosphate attachments
- Show ambivalent behavior toward water. Hydrocarbon tails are hydrophobic and the polar head (phosphate group with attachments) is hydrophilic.
- Cluster in water as their hydrophobic portions turn away from water. One such cluster, a *micelle*, assembles so the hydrophobic tails turn toward the water-free interior and the hydrophilic phosphate heads arrange facing outward in contact with water (see Campbell, Figure 5.13).
- Are major constituents of cell membranes. At the cell surface, phospholipids form a bilayer held together by hydrophobic interactions among the hydrocarbon tails. Phospholipids in water will spontaneously form such a bilayer.

C. Steroids

Steroids = Lipids which have four fused carbon rings with various functional groups attached.

Cholesterol is an important steroid.

- Is the precursor to many other steroids including vertebrate sex hormones and bile acids.
- Is a common component of animal cell membranes.
- Can contribute to atherosclerosis.
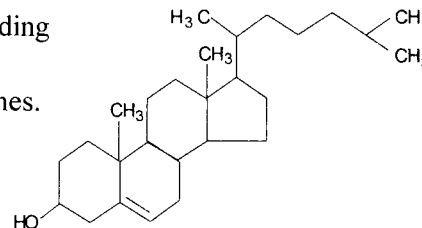
IV.   Proteins: The Molecular Tools of the Cell

Polypeptide chains = Polymers of amino acids that are arranged in a specific linear sequence and are linked by peptide bonds.

Protein = A macromolecule that consists of one or more *polypeptide chains* folded and coiled into specific conformations.

- Are abundant, making up 50% or more of cellular dry weight
- Have important and varied functions in the cell:

    1. Structural support
    2. Storage (of amino acids)
    3. Transport (e.g., hemoglobin)
    4. Signaling (chemical messengers)
    5. Cellular response to chemical stimuli (receptor proteins)
    6. Movement (contractile proteins)
    7. Defense against foreign substances and disease-causing organisms (antibodies)
    8. Catalysis of biochemical reactions (enzymes)

- Vary extensively in structure; each type has a unique three-dimensional shape (conformation)
- Though they vary in structure and function, they are commonly made of only 20 amino acid monomers.

## A.   A polypeptide is a polymer of amino acids connected in a specific sequence

Amino acid = Building block molecule of a protein; most consist of an asymmetric carbon, termed the *alpha carbon*, which is covalently bonded to a(n):

1. Hydrogen atom.
2. Carboxyl group.
3. Amino group.
4. Variable R group (side chain) specific to each amino acid. Physical and chemical properties of the side chain determine the uniqueness of each amino acid.
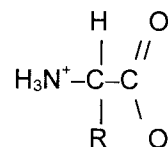
(At pH's normally found in the cell, both the carboxyl and amino groups are ionized.)

Amino acids contain both carboxyl and amino functional groups. Since one group acts as a weak acid and the other group acts as a weak base, an amino acid can exist in three ionic states. The pH of the solution determines which ionic state predominates.

Cation   Zwitterion   Anion
   (dipolar ion)
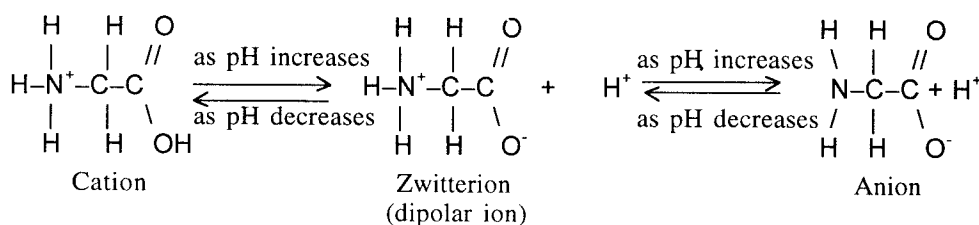
The twenty common amino acids can be grouped by properties of side chains (see Campbell, Figure 5.15):

1. Nonpolar side groups (hydrophobic). Amino acids with nonpolar groups are less soluble in water.

2. Polar side groups (hydrophilic). Amino acids with polar side groups are soluble in water. Polar amino acids can be grouped further into:

   a. Uncharged polar

   b. Charged polar

      • Acidic side groups. Dissociated carboxyl group gives these side groups a negative charge.

      • Basic side groups. An amino group with an extra proton gives these side groups a net positive charge.

Polypeptide chains are polymers that are formed when amino acid monomers are linked by peptide bonds (see Campbell, Figure 5.16).

Peptide bond = Covalent bond formed by a condensation reaction that links the carboxyl group of one amino acid to the amino group of another.

• Has polarity with an amino group on one end (*N-terminus*) and a carboxyl group on the other (*C-terminus*).

• Has a backbone of the repeating sequence –N–C–C–N–C–C–.
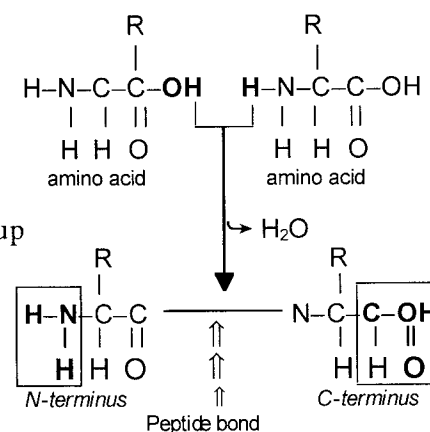
Polypeptide chains:

• Range in length from a few monomers to more than a thousand.

• Have unique linear sequences of amino acids.

B. A protein's function depends on its specific conformation

A protein's function depends upon its unique *conformation*.

Protein conformation = Three-dimensional shape of a protein.

Native conformation = Functional conformation of a protein found under normal biological conditions.

• Enables a protein to recognize and bind specifically to another molecule (e.g., hormone/receptor, enzyme/substrate, and antibody/antigen)

• Is a consequence of the specific linear sequence of amino acids in the polypeptide

• Is produced when a newly formed polypeptide chain coils and folds spontaneously, mostly in response to hydrophobic interactions

• Is stabilized by chemical bonds and weak interactions between neighboring regions of the folded protein

1. Four levels of protein structure

The correlation between form and function in proteins is an emergent property resulting from superimposed levels of protein structure (see Campbell, Figure 5.24):

• Primary structure

• Secondary structure

- Tertiary structure
- When a protein has two or more polypeptide chains, it also has quaternary structure.

a. Primary structure

Primary structure = Unique sequence of amino acids in a protein.

- Determined by genes
- Slight change can affect a protein's conformation and function (e.g., sickle-cell hemoglobin; see Campbell, Figure 5.19).
- Can be sequenced in the laboratory. A pioneer in this work was Frederick Sanger who determined the amino acid sequence in insulin (late 1940s and early 1950s). This laborious process involved:

  1) Determination of amino acid composition by complete acid hydrolysis of peptide bonds and separation of resulting amino acids by chromatography. Using these techniques, Sanger identified the amino acids and determined the relative proportions of each.

  2) Determination of amino acid sequence by partial hydrolysis with enzymes and other catalysts to break only specific peptide bonds. Sanger deductively reconstructed the primary structure from fragments with overlapping segments.

- Most of the sequencing process is now automated.

b. Secondary structure

Secondary structure = Regular, repeated coiling and folding of a protein's polypeptide backbone (see Campbell, Figure 5.20).

- Contributes to a protein's overall conformation.
- Stabilized by hydrogen bonds between peptide linkages in the protein's backbone (carbonyl and amino groups).
- The major types of secondary structure are alpha (α) helix and beta (β) pleated sheet.

1) Alpha (α) helix

   Alpha (α) helix = Secondary structure of a polypeptide that is a helical coil stabilized by hydrogen bonding between every fourth peptide bond (3.6 amino acids per turn).

   - Described by Linus Pauling and Robert Corey in 1951.
   - Found in fibrous proteins (e.g., α-keratin and collagen) for most of their length and in some portions of globular proteins.

2) Beta (β) pleated sheet

   Beta (β) pleated sheet = Secondary protein structure which is a sheet of antiparallel chains folded into accordion pleats.

   - Parallel regions are held together by either intrachain or interchain hydrogen bonds (between adjacent polypeptides).
   - Make up the dense core of many globular proteins (e.g., lysozyme) and the major portion of some fibrous proteins (e.g., fibroin, the structural protein of silk).

c. Tertiary structure

Tertiary structure = The three-dimensional shape of a protein. The irregular contortions of a protein are due to bonding between and among side chains (R groups) and to interaction between R groups and the aqueous environment (see Campbell, Figure 5.22).

Types of bonds contributing to tertiary structure are weak interactions and covalent linkage (both may occur in the same protein).
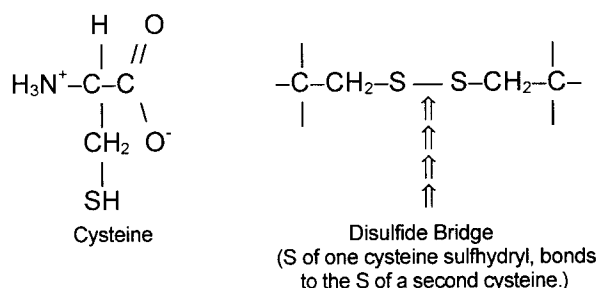
1) Weak interactions

Protein shape is stabilized by the cumulative effect of weak interactions. These weak interactions include:

- Hydrogen bonding between polar side chains.
- Ionic bonds between charged side chains.
- *Hydrophobic interactions* between nonpolar side chains in protein's interior.

Hydrophobic interactions = (Hydro = water; phobos = fear); the clustering of hydrophobic molecules as a result of their mutual exclusion from water.

2) Covalent linkage

Disulfide bridges form between two cysteine monomers brought together by folding of the protein. This is a strong bond that reinforces conformation.

$$
\begin{array}{cc}
\underset{\text{Cysteine}}{
\begin{array}{c}
\;\;\;\; H\;\;\; O\\
\;\;\;\; |\;\;\; // \\
H_3N^+\text{-C-C} \\
\;\;\;\; |\;\;\;\; \backslash \\
\;\;\;\; CH_2\;\; O^- \\
\;\;\;\; | \\
\;\;\;\; SH
\end{array}}
&
\underset{\substack{\text{Disulfide Bridge}\\ \text{(S of one cysteine sulfhydryl, bonds}\\ \text{to the S of a second cysteine.)}}}{
\begin{array}{c}
|\;\;\;\;\;\;\;\;\;\;\;\;\;\;\; | \\
\text{-C-CH}_2\text{-S} - \text{S-CH}_2\text{-C-} \\
|\;\;\;\;\;\;\;\;\; \Uparrow\;\;\;\;\;\;\; | \\
\;\;\;\;\;\;\;\;\;\;\; \Uparrow \\
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\;\;\;\;\;\;\;\;\;\;\; \Uparrow
\end{array}}
\end{array}
$$

d. Quaternary structure

Quaternary structure = Structure that results from the interactions between and among several polypeptides chains (subunits) (see Campbell, Figure 5.23).

- Example: Collagen, a fibrous protein with three helical polypeptides supercoiled into a triple helix; found in animal connective tissue, collagen's supercoiled quaternary structure gives it strength.
- Some globular proteins have subunits that fit tightly together. Example: Hemoglobin, a globular protein that has four subunits (two α chains and two β chains)

2. What determines protein conformation?

A protein's three-dimensional shape is a consequence of the interactions responsible for secondary and tertiary structure.

- This conformation is influenced by physical and chemical environmental conditions.
- If a protein's environment is altered, it may become *denatured* and lose its native conformation.

Denaturation = A process that alters a protein's native conformation and biological activity. Proteins can be denatured by:

- Transfer to an organic solvent. Hydrophobic side chains, normally inside the protein's core, move towards the outside. Hydrophilic side chains turn away from the solvent towards the molecule's interior.
- Chemical agents that disrupt hydrogen bonds, ionic bonds and disulfide bridges.
- Excessive heat. Increased thermal agitation disrupts weak interactions (see Campbell, Figure 5.25).

The fact that some denatured proteins return to their native conformation when environmental conditions return to normal is evidence that a protein's amino acid sequence (primary structure) determines conformation. It influences where and which interactions will occur as the molecule arranges into secondary and tertiary structure.

3. The protein-folding problem

Even though primary structure ultimately determines a protein's conformation, three-dimensional shape is difficult to predict solely on the basis of amino acid sequence. It is difficult to find the rules of protein folding because:

- Most proteins pass through several intermediate stages in the folding process; knowledge of the final conformation does not reveal the folding process required to create it.
- A protein's native conformation may be dynamic, alternating between several shapes.

Using recently developed techniques, researchers hope to gain new insights into protein folding:

- Biochemists can now track a protein as it passes through its intermediate stages during the folding process.
- *Chaperone proteins* have just been discovered that temporarily brace a folding protein.

Rules of protein folding are important to molecular biologists and the biotechnology industry. This knowledge should allow the design of proteins for specific purposes.

V.   Nucleic Acids: Informational Polymers

A. Nucleic acids store and transmit hereditary information

Protein conformation is determined by primary structure. Primary structure, in turn, is determined by *genes*; hereditary units that consist of DNA, a type of *nucleic acid.* There are two types of nucleic acids.
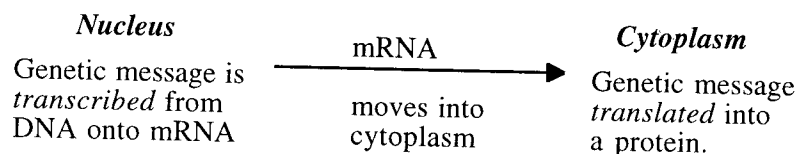
1. Deoxyribonucleic acid (DNA)

- Contains coded information that programs all cell activity.
- Contains directions for its own replication.
- Is copied and passed from one generation of cells to another.
- In eukaryotic cells, is found primarily in the nucleus.
- Makes up *genes* that contain instructions for protein synthesis. Genes do not directly make proteins, but direct the synthesis of mRNA.

2. Ribonucleic acid (RNA)

- Functions in the actual synthesis of proteins coded for by DNA.
- Sites of protein synthesis are on *ribosomes* in the cytoplasm.
- Messenger RNA (mRNA) carries encoded genetic message from the nucleus to the cytoplasm.
- The flow of genetic information goes from DNA → RNA → protein (see Campbell, Figure 5.26).

Nucleus	mRNA	*Cytoplasm*
Genetic message is *transcribed* from DNA onto mRNA	⟶ moves into cytoplasm	Genetic message *translated* into a protein.

B. A nucleic acid strand is a polymer of nucleotides

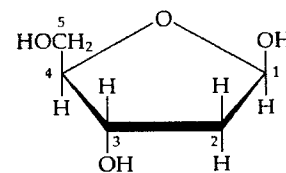*Nucleic acid* = Polymer of *nucleotides* linked together by condensation reactions.

Nucleotide = Building block molecule of a nucleic acid; made of (1) a five-carbon sugar covalently bonded to (2) a phosphate group and (3) a nitrogenous base.

1. Pentose (5-carbon sugar)

There are two pentoses found in nucleic acids: ribose and deoxyribose.
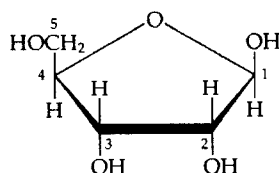
Ribose is the pentose in RNA.

Deoxyribose is the pentose in DNA. (It lacks the –OH group at the number two carbon.)

2. Phosphate

The phosphate group is attached to the number 5 carbon of the sugar.

3. Nitrogenous base

There are two families of *nitrogenous bases*:

Pyrimidine = Nitrogenous base characterized by a six-membered ring made up of carbon and nitrogen atoms. For example:

- Cytosine (C)
- Thymine (T); found only in DNA
- Uracil (U); found only in RNA

Purine = Nitrogenous base characterized by a five-membered ring fused to a six-membered ring. For example:

- Adenine (A)
- Guanine (G)

Nucleotides have various functions:

- Are monomers for nucleic acids.
- Transfer chemical energy from one molecule to another (e.g., ATP).
- Are electron acceptors in enzyme-controlled redox reactions of the cell (e.g., NAD).

A nucleic-acid polymer or polynucleotise, results from joining nucleotides together by covalent bonds called *phosphodiester linkages*. The bond is formed between the phosphate of one nucleotide and the sugar of the next.

Phosphate
Base
Sugar

- Results in a backbone with a repeating pattern of sugar-phosphate-sugar-phosphate.
- Variable nitrogenous bases are attached to the sugar-phosphate backbone.
- Each gene contains a unique linear sequence of nitrogenous bases which codes for a unique linear sequence of amino acids in a protein.
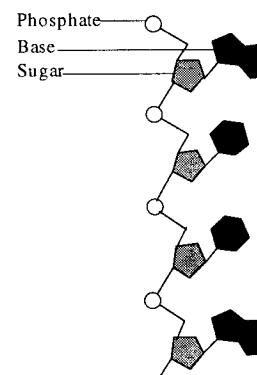
C. Inheritance is based on precise replication of the DNA double helix

In 1953, James Watson and Francis Crick proposed the *double helix* as the three dimensional structure of DNA.

- Consists of two nucleotide chains wound in a double helix.
- Sugar-phosphate backbones are on the outside of the helix.
- The two polynucleotide strands of DNA are held together by hydrogen bonds between the paired nitrogenous bases and by van der Waals attraction between the stacked bases (see Campbell, Figure 5.28).
- Base-pairing rules are that adenine (A) always pairs with thymine (T); guanine (G) always pairs with cytosine (C).
- Two strands of DNA are complimentary and thus can serve as templates to make new complementary strands. It is this mechanism of precise copying that makes inheritance possible.
- Most DNA molecules are long, containing thousands or millions of base pairs.

D. We can use DNA and proteins as tape measures of evolution

Closely related species have more similar sequences of DNA and amino acids, than more distantly related species. Using this type of molecular evidence, biologists can deduce evolutionary relationships among species.

> Chapters 16 and 17 are devoted to DNA and protein synthesis. Since any discussion of DNA function must include the details of DNA structure, it may be more practical and less time-consuming to cover nucleic acids later in the course.

REFERENCES

Alberts, B., et al. *Essential Cell Biology: An Introduction to the Molecular Biology of the Cell.* New York: Garland Publishing, Inc., 1998.

Campbell, N., et al. *Biology.* 5th ed. Menlo Park, California: Benjamin/Cummings, 1998.

Lehninger, A.L., D.L. Nelson and M.M. Cox. *Principles of Biochemistry.* 2nd ed. New York: Worth, 1993.

Brown, T.L., H. E. Le May, Jr., and B. Bursten. *Chemistry: The Central Science.* 7th Ed. Upper Saddle River, New Jersey: Prentice Hall, 1997.