Chapter 5

The Structure and Function of Large Biological Molecules

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Lectures by Chris Romero, updated by Erin Barley with contributions from Joan Sharp
Overview: The Molecules of Life

• All living things are made up of **four classes** of large biological molecules: carbohydrates, lipids, proteins, and nucleic acids

• **Macromolecules** are large molecules composed of **thousands** of covalently connected atoms

• Molecular **structure** and **function** are **inseparable**
Macromolecules are polymers, built from monomers

- **Polymer** is a long molecule consisting of **many similar** building blocks.
- These small building-block molecules are called **monomers**.
- **Three** of the four classes of life’s organic molecules are **polymers**:
  - Carbohydrates
  - Proteins
  - Nucleic acids
A condensation reaction or more specifically a dehydration reaction occurs when two monomers bond together through the loss of a water molecule.

Polymers are disassembled to monomers by hydrolysis, a reaction that is essentially the reverse of the dehydration reaction.

Enzymes are macromolecules that speed up chemical reactions.
Dehydration removes a water molecule, forming a new bond.

Hydrolysis adds a water molecule, breaking a bond.

(a) Dehydration reaction in the synthesis of a polymer

(b) Hydrolysis of a polymer
The Diversity of Polymers

- Each cell has **thousands** of different kinds of macromolecules.
- Macromolecules **vary** among cells of an organism, vary more within a species, and vary even more between species.
- An immense **variety** of polymers can be built **from a small set of monomers**.
Carbohydrates serve as fuel and building material

- **Carbohydrates** include **sugars** and the **polymers** of sugars
- The simplest carbohydrates are **monosaccharides**, or **single sugars**
- Carbohydrate macromolecules are **polysaccharides**, polymers **composed of many sugar building blocks**
Sugars

- **Monosaccharides** have molecular formulas that are usually *multiples of CH₂O*

- Glucose \((C_6H_{12}O_6)\) is the most common monosaccharide

- Monosaccharides are classified by
  - The *location of the carbonyl group*
  - The *number of carbons* in the carbon skeleton
<table>
<thead>
<tr>
<th></th>
<th>Trioses ($\text{C}_3\text{H}_6\text{O}_3$)</th>
<th>Pentoses ($\text{C}<em>5\text{H}</em>{10}\text{O}_5$)</th>
<th>Hexoses ($\text{C}<em>6\text{H}</em>{12}\text{O}_6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aldoses</strong></td>
<td><img src="image" alt="Glyceraldehyde" /></td>
<td><img src="image" alt="Ribose" /></td>
<td><img src="image" alt="Glucose" /></td>
</tr>
<tr>
<td><strong>Ketoses</strong></td>
<td><img src="image" alt="Dihydroxyacetone" /></td>
<td><img src="image" alt="Ribulose" /></td>
<td><img src="image" alt="Fructose" /></td>
</tr>
</tbody>
</table>
• Though often drawn as linear skeletons, in aqueous solutions many sugars form **rings**

• Monosaccharides serve as a **major fuel for cells** and as **raw material for building molecules**

• A **disaccharide** is formed when a dehydration reaction joins two monosaccharides

• This covalent bond is called **a glycosidic linkage**
(a) Dehydration reaction in the synthesis of maltose

(b) Dehydration reaction in the synthesis of sucrose
Polysaccharides

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

- The structure and function of a polysaccharide are determined by its sugar monomers and the positions of glycosidic linkages.

- **Starch**, a storage polysaccharide of plants, consists entirely of glucose monomers.

- Plants store surplus starch as granules within chloroplasts and other plastids.
(a) Starch: a plant polysaccharide

(b) Glycogen: an animal polysaccharide
Structural Polysaccharides

- **Glycogen** is a storage polysaccharide in animals.
- Humans and other vertebrates store glycogen mainly in liver and muscle cells.
- The polysaccharide **cellulose** is a major component of the tough wall of plant cells.
- Like starch, **cellulose** is a **polymer of glucose**, but the **glycosidic linkages differ**.

[Animation: Polysaccharides]
The arrangement of cellulose in plant cell walls
• Enzymes that digest starch by hydrolyzing $\alpha$ linkages can’t hydrolyze $\beta$ linkages in cellulose.

• Cellulose in human food passes through the digestive tract as insoluble fiber.

• Some microbes use enzymes to digest cellulose.

• Many herbivores, from cows to termites, have symbiotic relationships with these microbes.
Chitin, another structural polysaccharide, is found in the exoskeleton of arthropods.

(a) The structure of the chitin monomer.

(b) Chitin forms the exoskeleton of arthropods.

(c) Chitin is used to make a strong and flexible surgical thread.

Chitin also provides structural support for the cell walls of many fungi.
Lipids are a diverse group of hydrophobic molecules

- Lipids are the **one** class of large biological molecules that **do not form polymers**
- The unifying feature of lipids is **having little or no affinity for water**
- Lipids are **hydrophobic** because they consist mostly of hydrocarbons, which form nonpolar covalent bonds
- The most biologically important lipids are **fats**, **phospholipids**, and **steroids**
• **Fats** are constructed from **two types** of smaller molecules: **glycerol** and **fatty acids**

• **Glycerol** is a **three-carbon alcohol** with a hydroxyl group attached to each carbon

• A **fatty acid** consists of a **carboxyl group attached to a long carbon skeleton**
Fatty acid (palmitic acid)

Glycerol
(a) Dehydration reaction in the synthesis of a fat

Ester linkage

(b) Fat molecule (triacylglycerol)

In a fat, three fatty acids are joined to glycerol by an ester linkage, creating a triacylglycerol, or triglyceride.
Fatty acids vary **in length** (number of carbons) and **in the number and locations of double bonds**

**Saturated fatty acids** have the **maximum number of hydrogen atoms** possible and no double bonds

**Unsaturated fatty acids** have **one or more double bonds**
Fats made from saturated fatty acids are called **saturated fats**, and are **solid at room temperature**. Most animal fats are saturated.

Fats made from unsaturated fatty acids are called **unsaturated fats** or **oils**, and are **liquid at room temperature**. Plant fats and fish fats are usually unsaturated.
• A diet rich in saturated fats may contribute to cardiovascular disease through plaque deposits.

• Hydrogenation is the process of converting unsaturated fats to saturated fats by adding hydrogen.

• Hydrogenating vegetable oils also creates unsaturated fats with trans double bonds (margarines, spreads).

• These trans fats may contribute more than saturated fats to cardiovascular disease.
• The major **function of fats** is **energy storage**

• Humans and other mammals store their fat in **adipose cells**

• Adipose tissue also **cushions** vital organs and **insulates** the body
Phospholipids

- In a phospholipid, two fatty acids and a phosphate group are attached to glycerol.
- The two fatty acid tails are hydrophobic, but the phosphate group and its attachments form a hydrophilic head.
• When phospholipids are added to water, they self-assemble into a **bilayer**, with the **hydrophobic** tails pointing toward the interior.

• The structure of phospholipids results in a bilayer arrangement found in cell membranes.

• Phospholipids are the **major component of all cell membranes**.
Bilayer structure formed by self-assembly of phospholipids in an aqueous environment.
Steroids are lipids characterized by a carbon skeleton consisting of **four** fused rings.
Cholesterol, an important steroid, is a component in animal cell membranes. Although cholesterol is essential in animals, high levels in the blood may contribute to cardiovascular disease.
Proteins have many structures, resulting in a wide range of functions

- Proteins account for more than 50% of the dry mass of most cells

- Protein functions include structural support, storage, transport, cellular communications, movement, and defense against foreign substances
<table>
<thead>
<tr>
<th>Type of Protein</th>
<th>Function</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enzymatic proteins</td>
<td>Selective acceleration of chemical reactions</td>
<td>Digestive enzymes</td>
</tr>
<tr>
<td>Structural proteins</td>
<td>Support</td>
<td>Silk fibers; collagen and elastin in animal connective tissues; keratin in hair, horns, feathers, and other skin appendages</td>
</tr>
<tr>
<td>Storage proteins</td>
<td>Storage of amino acids</td>
<td>Ovalbumin in egg white; casein, the protein of milk; storage proteins in plant seeds</td>
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<tr>
<td>Transport proteins</td>
<td>Transport of other substances</td>
<td>Hemoglobin, transport proteins</td>
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<tr>
<td>Hormonal proteins</td>
<td>Coordination of an organism’s activities</td>
<td>Insulin, a hormone secreted by the pancreas</td>
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<tr>
<td>Receptor proteins</td>
<td>Response of cell to chemical stimuli</td>
<td>Receptors in nerve cell membranes</td>
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<tr>
<td>Contractile and motor proteins</td>
<td>Movement</td>
<td>Actin and myosin in muscles, proteins in cilia and flagella</td>
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<tr>
<td>Defensive proteins</td>
<td>Protection against disease</td>
<td>Antibodies combat bacteria and viruses.</td>
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• Enzymes are a type of protein that acts as a catalyst to speed up chemical reactions

• Enzymes can perform their functions repeatedly, functioning as workhorses that carry out the processes of life

Polypeptides

• Polypeptides are polymers built from the same set of 20 amino acids

• A protein consists of one or more polypeptides
Amino Acid Monomers

- **Amino acids** are organic molecules with **carboxyl and amino groups**
- Amino acids differ in their properties due to differing side chains, called R groups

![Diagram of amino acid structure](image_url)
- Amino acids are linked by peptide bonds
- A polypeptide is a polymer of amino acids
- Polypeptides range in length from a few to more than a thousand monomers
- Each polypeptide has a unique linear sequence of amino acids
A functional protein consists of one or more polypeptides twisted, folded, and coiled into a unique shape.

The sequence of amino acids determines a protein’s three-dimensional structure.

A protein’s structure determines its function.
Four Levels of Protein Structure

- The **primary** structure of a protein is its unique sequence of amino acids.
- **Secondary** structure, found in most proteins, consists of coils and folds in the polypeptide chain.
- **Tertiary** structure is determined by interactions among various side chains (R groups).
- **Quaternary** structure results when a protein consists of multiple polypeptide chains.
• **Primary structure**, the sequence of amino acids in a protein, is like the order of letters in a long word.

• Primary structure is determined by **inherited genetic information**.
The coils and folds of secondary structure result from hydrogen bonds between repeating constituents of the polypeptide backbone.
• **Tertiary structure** is determined by interactions between R groups, rather than interactions between backbone constituents.

• These *interactions between R groups* include hydrogen bonds, ionic bonds, **hydrophobic interactions**, and van der Waals interactions.

• **Strong covalent bonds** called **disulfide bridges** may reinforce the protein’s structure.
Tertiary Structure  Quaternary Structure
- **Quaternary structure** results when two or more polypeptide chains form one macromolecule.

- **Collagen** is a **fibrous protein** consisting of three polypeptides coiled like a rope.

- **Hemoglobin** is a **globular protein** consisting of four polypeptides: two alpha and two beta chains.
Hemoglobin

Heme

Iron

α subunit

β subunit

β subunit

α subunit

Collagen
Normal hemoglobin

Val His Leu Thr Pro Glu Glu

1 2 3 4 5 6 7

Primary structure

Secondary and tertiary structures

Quaternary structure

Normal hemoglobin (top view)

Function

Molecules do not associate with one another; each carries oxygen.

Red blood cell shape

Normal red blood cells are full of individual hemoglobin molecules, each carrying oxygen.

10 µm

Sickle-cell hemoglobin

Val His Leu Thr Pro Val Glu

1 2 3 4 5 6 7

Primary structure

Secondary and tertiary structures

Exposed hydrophobic region

Quaternary structure

Sickle-cell hemoglobin

Function

Molecules interact with one another and crystallize into a fiber; capacity to carry oxygen is greatly reduced.

Red blood cell shape

Fibers of abnormal hemoglobin deform red blood cell into sickle shape.

10 µm
What Determines Protein Structure?

- In addition to primary structure, physical and chemical conditions can affect protein structure.

- **Alterations in pH, salt concentration, temperature, or other environmental factors can cause a protein to unravel.**

- This loss of a protein’s native structure is called **denaturation** (though it is **reversible** process).

- A **denatured protein is biologically inactive**.
Fig. 5-23

Normal protein → Denaturation → Renaturation → Denatured protein
Nucleic acids store and transmit hereditary information

- The amino acid **sequence** of a polypeptide is programmed by a unit of inheritance called a **gene**
- Genes are **made of** DNA, a **nucleic acid**
The Roles of Nucleic Acids

• There are two types of nucleic acids:
  – Deoxyribonucleic acid (DNA)
  – Ribonucleic acid (RNA)

• DNA provides directions for its own replication

• DNA directs synthesis of messenger RNA (mRNA) and, through mRNA, controls protein synthesis

• Protein synthesis occurs in ribosomes
Fig. 5-26-3

1. Synthesis of mRNA in the nucleus

2. Movement of mRNA into cytoplasm via nuclear pore

3. Synthesis of protein

DNA  mRNA  NUCLEUS  CYTOPLASM  Ribosome  mRNA  Amino acids  Polypeptide
The Structure of Nucleic Acids

- Each nucleic acid molecule is made of monomers called **nucleotides**
- Each nucleotide consists of a nitrogenous base, a pentose sugar, and a phosphate group
- The portion of a nucleotide **without the phosphate group** is called a **nucleoside**
(a) Polynucleotide, or nucleic acid

(b) Nucleotide

(c) Nucleoside components: sugars

Nitrogenous bases
- Pyrimidines
  - Cytosine (C)
  - Thymine (T, in DNA)
  - Uracil (U, in RNA)
- Purines
  - Adenine (A)
  - Guanine (G)

Sugars
- Deoxyribose (in DNA)
- Ribose (in RNA)
Nucleotide Monomers

- Nucleoside = nitrogenous base + sugar

- There are **two families** of nitrogenous bases:
  - **Pyrimidines** (cytosine, thymine, and uracil) have a single six-membered ring
  - **Purines** (adenine and guanine) have a six-membered ring fused to a five-membered ring

- In DNA, the sugar is **deoxyribose**; in RNA, the sugar is **ribose**
The DNA double helix and its replication

- Sugar-phosphate backbones
- Base pair (joined by hydrogen bonding)
- Old strands
- Nucleotide about to be added to a new strand
- New strands

Base pair (joined by hydrogen bonding)
The linear sequences of nucleotides in DNA molecules are passed from parents to offspring.

Two closely related species are more similar in DNA than are more distantly related species.

Molecular biology can be used to assess evolutionary kinship.
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<th>Carbohydrates serve as fuel and building material</th>
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<td><strong>Monosaccharide monomer</strong></td>
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<tr>
<th>Concept 5.3</th>
<th>Lipids are a diverse group of hydrophobic molecules</th>
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<td><strong>Components</strong></td>
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<td><strong>Glycerol</strong></td>
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<td><strong>3 fatty acids</strong></td>
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<td><strong>Triacylglycerols</strong></td>
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<thead>
<tr>
<th>Concept 5.4</th>
<th>Proteins include a diversity of structures, resulting in a wide range of functions</th>
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<tbody>
<tr>
<td><strong>Components</strong></td>
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<td><strong>Amino acid monomer</strong></td>
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<tr>
<td><strong>20 types</strong></td>
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<td><strong>Enzymes</strong></td>
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<td><strong>Structural proteins</strong></td>
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<td><strong>Storage proteins</strong></td>
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<td><strong>Transport proteins</strong></td>
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<td><strong>Hormones</strong></td>
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<td><strong>Receptor proteins</strong></td>
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<td><strong>Motor proteins</strong></td>
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<td><strong>Defensive proteins</strong></td>
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<tr>
<th>Concept 5.5</th>
<th>Nucleic acids store, transmit, and help express hereditary information</th>
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<tbody>
<tr>
<td><strong>Components</strong></td>
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<td><strong>DNA</strong></td>
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<td><strong>Phosphate group</strong></td>
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<td><strong>Sugar</strong></td>
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<tr>
<td><strong>Nucleotide monomer</strong></td>
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<td><strong>RNA</strong></td>
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<td><strong>Phosphate group</strong></td>
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<td><strong>Sugar</strong></td>
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<td><strong>Nucleotide monomer</strong></td>
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</table>
**Concept 5.2**
Carbohydrates serve as fuel and building material

<table>
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<tr>
<th>Large Biological Molecules</th>
<th>Components</th>
<th>Examples</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monosaccharides:</strong> glucose, fructose</td>
<td><img src="image" alt="Monosaccharide monomer" /></td>
<td></td>
<td>Fuel; carbon sources that can be converted to other molecules or combined into polymers</td>
</tr>
<tr>
<td><strong>Disaccharides:</strong> lactose, sucrose</td>
<td></td>
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</tbody>
</table>
| **Polysaccharides:** | | • Cellulose (plants)  
  • Starch (plants)  
  • Glycogen (animals)  
  • Chitin (animals and fungi) | • Strengthens plant cell walls  
  • Stores glucose for energy  
  • Stores glucose for energy  
  • Strengthens exoskeletons and fungal cell walls |

**Concept 5.3**
Lipids are a diverse group of hydrophobic molecules

<table>
<thead>
<tr>
<th>Large Biological Molecules</th>
<th>Components</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Glycerol</strong></td>
<td><img src="image" alt="Glycerol" /></td>
<td><strong>Triacylglycerols</strong> (fats or oils): glycerol + 3 fatty acids</td>
<td>Important energy source</td>
</tr>
</tbody>
</table>
| **Phospholipids:** phosphate group + 2 fatty acids | ![Phospholipid](image) | Lipid bilayers of membranes  
  **Hydrophilic heads**  
  **Hydrophobic tails** | |
| **Steroids:** four fused rings with attached chemical groups | ![Steroid backbone](image) | • Component of cell membranes (cholesterol)  
  • Signaling molecules that travel through the body (hormones) | |
<table>
<thead>
<tr>
<th>Large Biological Molecules</th>
<th>Components</th>
<th>Examples</th>
<th>Functions</th>
</tr>
</thead>
</table>
| **CONCEPT 5.4** | ![Amino acid monomer](image) | • Enzymes  
• Structural proteins  
• Storage proteins  
• Transport proteins  
• Hormones  
• Receptor proteins  
• Motor proteins  
• Defensive proteins | • Catalyze chemical reactions  
• Provide structural support  
• Store amino acids  
• Transport substances  
• Coordinate organismal responses  
• Receive signals from outside cell  
• Function in cell movement  
• Protect against disease |
| **CONCEPT 5.5** | ![DNA structure](image) | **DNA:**  
• Sugar = deoxyribose  
• Nitrogenous bases = C, G, A, T  
• Usually double-stranded | Stores hereditary information |
| | ![RNA structure](image) | **RNA:**  
• Sugar = ribose  
• Nitrogenous bases = C, G, A, U  
• Usually single-stranded | Various functions during gene expression, including carrying instructions from DNA to ribosomes |
<table>
<thead>
<tr>
<th>Monomers or components</th>
<th>Polymer or larger molecule</th>
<th>Type of linkage</th>
</tr>
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<td>Sugars</td>
<td>Monosaccharides</td>
<td>Polysaccharides</td>
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<td>Lipids</td>
<td>Fatty acids</td>
<td>Triacylglycerols</td>
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<td>Proteins</td>
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<td>Polypeptides</td>
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<td>Polynucleotides</td>
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