Chemical Level of Organization

The Atom and Its Subatomic Particles

Molecules

Electrons and Isotopes
Each energy level can hold a certain maximum number of electrons

This is determined by the formula $X = 2n^2$

$X$ is the maximum number of electrons in energy level $n$

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**Ions and Ionic Bonds**

The loss of an electron from a sodium atom, forming a sodium cation

**Sodium atom, Na (reactive)**

The gain of an electron by a chlorine atom, forming a chloride anion

**Chlorine atom, Cl (reactive)**

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**Reactive elements**

Two examples of reactive elements, which have unfilled outermost energy levels

**Hydrogen**

- Atomic number: 1
- Mass number: 1 electron

**Lithium**

- Atomic number: 3
- Mass number: 6 (2 protons + 3 neutrons)
- 3 electrons

---

**Inert elements**

Two examples of inert elements, which do not react in chemical processes because their outermost energy levels are filled

**Helium**

- Atomic number: 2
- Mass number: 4 (2 protons + 2 neutrons)
- 2 electrons

**Neon**

- Atomic number: 10
- Mass number: 10 (10 protons + 10 neutrons)
- 10 electrons
### Covalent Bonds

Molecules, which consist of one or more elements bound by covalent bonds resulting from the sharing of electrons.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrogen</strong> (H₂)</td>
<td>Hydrogen atoms aren’t found as individuals—they exist as molecules, each containing a pair of hydrogen atoms. The two atoms share their electrons to fill their outer energy levels, and the electron pair orbits both nuclei. One electron is contributed by each atom, so this is called a simple covalent bond.</td>
</tr>
<tr>
<td><strong>Oxygen</strong> (O₂)</td>
<td>An oxygen atom has 6 electrons in its outer energy level. By forming a double covalent bond with another oxygen atom, an oxygen molecule is created with a stable outer energy level.</td>
</tr>
<tr>
<td><strong>Carbon dioxide</strong> (CO₂)</td>
<td>A carbon atom has 4 electrons in its outer energy level, so it needs to gain 4 from other atoms to achieve stability. In a molecule of carbon dioxide, a carbon atom shares a pair of electrons with each of two oxygen atoms and forms two double covalent bonds.</td>
</tr>
</tbody>
</table>

### Polar Covalent Bonds

A water molecule, which is a polar molecule (has positively and negatively charged portions) that contains polar covalent bonds.

### Hydrogen Bonds

The attraction of hydrogen bonds, which occur between the small positive and negative charges on different water molecules.
Types of Chemical Reactions
Decomposition, Synthesis, Exchange

**Decomposition reactions**

Decomposition is a reaction that breaks a molecule into smaller fragments. You could represent a simple decomposition reaction as:

\[ AB \rightarrow A + B \]

Decomposition reactions occur outside cells as well as inside them. For example, a typical meal contains molecules of fats, sugars, and proteins that are too large and too complex to be absorbed and used by your body. Decomposition reactions in the digestive tract break these molecules down into smaller fragments before absorption begins.

Decomposition reactions involving water are important in the breakdown of complex molecules in the body. In hydrolysis (hydration—water breaks a bond), one of the bonds in a complex molecule is broken, and the components of a water molecule (H and OH) are added to the resulting fragments:

\[ A-B + H_2O \rightarrow A^+ + OH^- + H_2O \]

Collectively, the decomposition reactions of complex molecules within the body’s cells and tissues are referred to as catabolism (meta-Tab—tissue; Astat, a throwing down). When a covalent bond—a form of potential energy—is broken, it releases kinetic energy that can perform work. By harnessing the energy released in this way, cells perform vital functions such as growth, movement, and reproduction.

**Chemical reactions absorbed**

Energy transfer and use

Typical cell

Essential activities
- Maintenance and repair
- Growth
- Division
- Special functions

The cell, a “chemical factory” that is the site of all the chemical reactions that constitute metabolism.
**Synthesis reactions**

Synthesis (sin-thé-sis) is the opposite of decomposition. A synthesis reaction assembles smaller molecules into larger molecules. A simple synthetic reaction could be diagrammed as:

\[ A + B \rightarrow AB \]

Synthesis reactions may involve the combining of atoms or molecules to form even larger products. The formation of water from hydrogen and oxygen molecules is a synthesis reaction. Synthesis always involves the formation of new chemical bonds, whether the reactants are atoms or molecules.

Dehydration synthesis, or condensation, is the formation of a complex molecule by the removal of a small molecule:

\[ A + OH\cdot\text{cond} + B \rightarrow AB + H_{2}O \]

Dehydration synthesis is therefore the opposite of hydrolysis. We will encounter examples of both reactions in later sections.

Collectively, the synthesis of new molecules within the body’s cells and tissues is known as anabolism (an’ah-bal-izm; anabol, a building up). Because it takes energy to create a chemical bond, anabolism is usually considered an “uphill” process. Cells must balance their energy budgets, with catabolism providing the energy to support anabolism and other vital functions.

Chemical reactions are reversible (at least theoretically), so if:

\[ A + B \rightarrow AB \text{ then } AB \rightarrow A + B \]

Many important biological reactions are freely reversible. Such reactions can be represented as an equation:

\[ A + B \leftrightarrow AB \]

**Enzymes**

The action of protein catalysts called enzymes in promoting a chemical reaction by lowering its activation energy

In the external environment, extreme conditions can provide the activation energy. For example, complex sugars can be broken down in a laboratory by boiling them in an acidic solution.

Specific enzymes lower the activation energy requirements so that important reactions will occur.

**An exchange reaction**

In an exchange reaction, parts of the reacting molecules are shuffled around to produce new products:

\[ AB + CD \rightarrow AD + CB \]

Although the reactants and products contain the same components (A, B, C, and D), those components are present in different combinations. In an exchange reaction, the reactant molecules AB and CD must break apart (a decomposition) before they can interact with each other to form AD and CB (a synthesis).

**SUMMARY TABLE 2-9: CLASSES OF INORGANIC AND ORGANIC COMPOUNDS**

<table>
<thead>
<tr>
<th>Class</th>
<th>Building Blocks</th>
<th>Sources</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INORGANIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Hydrogen and oxygen atoms</td>
<td>Absorbed as liquid water or generated by metabolism</td>
<td>Solvent, transport medium for dissolved materials; heat, cooling through evaporation; medium for chemical reactions; reactant in hydrolysis</td>
</tr>
<tr>
<td>Acids, bases, salts</td>
<td>H⁺, O⁻, substrates and ions</td>
<td>Obtained from the diet or generated by metabolism</td>
<td>Structural components, buffers, source of ions</td>
</tr>
<tr>
<td>Dissolved gases</td>
<td>O, N, and other elements</td>
<td>Atmosphere</td>
<td>O₂ required for cellular respiration, CO₂ generated by cells as a waste product; NO, chemical messenger involved in cardiovascular, neuro, and lymphatic systems</td>
</tr>
<tr>
<td><strong>ORGANIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbohydrates</td>
<td>C, H, O, in some cases N, CH₃CHO in a 1:2:2 ratio</td>
<td>Obtained from the diet or manufactured in the body</td>
<td>Energy source: some structural sites when attached to lipids or proteins, energy storage</td>
</tr>
<tr>
<td>Lipids</td>
<td>C, H, O, in some cases N, CH₂CO in a 2:2:1 ratio</td>
<td>Obtained from the diet or manufactured in the body</td>
<td>Energy source: energy storage, insulation, structural components, chemical messenger, protection</td>
</tr>
<tr>
<td>Proteins</td>
<td>C, H, N, O, S, commonly</td>
<td>20 common amino acids</td>
<td>28-hour amino acid cycle, synthesized or manufactured in the body, either must be obtained from the diet</td>
</tr>
<tr>
<td>Nucleic acids</td>
<td>C, H, N, O, and P, nucleotides</td>
<td>Composed of phosphates, sugars, and nitrogenous bases</td>
<td>Obtained from the diet or manufactured in the body</td>
</tr>
<tr>
<td>High-energy compounds</td>
<td>Composed of phosphates by high-energy bonds</td>
<td>Synthesized by all cells</td>
<td>Storage or transfer of energy</td>
</tr>
</tbody>
</table>
Water

Many Compounds Dissociate in Water

Electrolytes - Ions Conducting Electrical Currents

$H^+$ in Solution - The pH Scale

Important Properties of Water

Lubrication
Water is an effective lubricant because there is little friction between water molecules. Thin even a thin layer of water between two opposing surfaces prevents them from rubbing against one another, and therefore reduces friction. In this case, water reduces friction within joints and in body cavities.

Nonsolvency
In our bodies, chemical reactions occur in water, and water molecules are also participants in some reactions, including hydrolysis and dehydration synthesis.

High heat capacity
Heat capacity is the ability to absorb and retain heat. Water has an unusually high heat capacity because water molecules in the liquid state are attracted to one another through hydrogen bonding.

Solubility
A relatively large number of inorganic and organic molecules will dissolve in water. The individual particles become dispersed within the water, and the result is a solution—a uniform mixture of two or more substances. Water can dissolve large numbers of other substances, ions, or molecules are dispersed to collate the network; the dispersed substances are the solutes. In aqueous solutions, water is the solvent.

Many Compounds Dissociate in Water

The roles of hydration spheres in the ionization or dissociation of an ionic compound (center) and in solutions of an organic molecule containing polar covalent bonds (right).

Electrolytes - Ions Conducting Electrical Currents

The movement of sodium and chloride ions, dissociated from the electrolyte sodium chloride, when subjected to an electric field.

Important Electrolytes That Dissociate in Body Fluids

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Ions Released</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl (sodium chloride)</td>
<td>$Na^+ + Cl^-$</td>
</tr>
<tr>
<td>KCl (potassium chloride)</td>
<td>$K^+ + Cl^-$</td>
</tr>
<tr>
<td>CaPO$_4$ (calcium phosphate)</td>
<td>$Ca^{2+} + PO_4^{3-}$</td>
</tr>
<tr>
<td>NaHCO$_3$ (sodium bicarbonate)</td>
<td>$Na^+ + HCO_3^-$</td>
</tr>
<tr>
<td>MgCl$_2$ (magnesium chloride)</td>
<td>$Mg^{2+} + 2Cl^-$</td>
</tr>
<tr>
<td>Na$_2$HPO$_4$ (sodium hydrogen phosphate)</td>
<td>$2Na^+ + HPO_4^{2-}$</td>
</tr>
<tr>
<td>Na$_2$SO$_4$ (sodium sulfate)</td>
<td>$2Na^+ + SO_4^{2-}$</td>
</tr>
</tbody>
</table>

$H^+$ in Solution - The pH Scale

The dissociation of a water molecule into a hydrogen ion, $H^+$, and a hydroxide ion, $OH^-$. The pH scale is a measure of the acidity or basicity of a solution. pH is defined as the negative logarithm of the hydrogen ion concentration ($[H^+]$).

A solution with a pH below 7 is acidic (pH < 7), meaning it contains more hydrogen ions than hydroxide ions.
A solution with a pH of 7 is said to be neutral, because it contains equal numbers of hydrogen and hydroxide ions.
A solution with a pH above 7 is basic, or alkaline (pH > 7), meaning that it has more hydroxide ions than hydrogen ions.

*One liter of pure water contains about 0.0000001 mol of hydrogen ions and an equal number of hydroxide ions. In other words, the concentration of hydrogen ions in a solution of pure water is $0.0000001$ mol per liter. This can be written as $[H^+] = 10^{-7}$ mol/L. The brackets around the $H^+$ signify "the concentration of," another example of chemical notation.
### Acids

- Hydrochloric acid (HCl), a strong acid because it releases hydrogen ions
  \[ \text{HCl} \rightarrow \text{H}^+ + \text{Cl}^- \]

### Bases

- Sodium hydroxide (NaOH), as a strong base because it releases hydroxide ions that remove hydrogen ions from solution
  \[ \text{NaOH} \rightarrow \text{Na}^+ + \text{OH}^- \]

### Buffers

- Carbonic acid, a weak acid in body fluids that reversibly dissociates into hydrogen ion and a bicarbonate ion
  \[ \text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^- \]

### Salts

- NaCl, a salt—an ionic compound consisting of any cation except a hydroxide ion and any anion except a hydronium ion.
  \[ \text{NaCl} \rightarrow \text{Na}^+ + \text{Cl}^- \]

### Functional Groups

- **Important Functional Groups of Organic Compounds**

<table>
<thead>
<tr>
<th>Functional Group</th>
<th>Structural Formula</th>
<th>Importance</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carboxylic acid group, (-\text{COOH})</td>
<td>[ R-C=O-R' ]</td>
<td>Acts as an acid, releasing H+ to become R-CO2-</td>
<td>- Fatty acids&lt;br&gt;- Amino acids</td>
</tr>
<tr>
<td>Amino group, (-\text{NH}_2)</td>
<td>[ R-N-H ]</td>
<td>Can accept or release H+, depending on pH; can form bonds with other molecules</td>
<td>- Amino acids</td>
</tr>
<tr>
<td>Hydroxyl group, (-\text{OH})</td>
<td>[ R-O-H ]</td>
<td>May link molecules through dehydration synthesis; hydrogen bonding between hydroxyl groups and water molecules affect solubility</td>
<td>- Carbohydrates&lt;br&gt;- Fatty acids&lt;br&gt;- Amino acids</td>
</tr>
<tr>
<td>Phosphate group, (-\text{PO}_4)</td>
<td>[ R-P=O-R' ]</td>
<td>May link other molecules to form larger structures; may store energy</td>
<td>- Phospholipids&lt;br&gt;- Nucleic acids&lt;br&gt;- High-energy compounds</td>
</tr>
</tbody>
</table>

*The term R groups used to denote the rest of the molecules, whatever they might be. The R group is also known as a side chain.*

### Carbohydrates

#### Carbohydrates in the Body

<table>
<thead>
<tr>
<th>Structural Class</th>
<th>Examples</th>
<th>Primary Function</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monosaccharides</strong> (simple sugars)</td>
<td>Glucose, fructose</td>
<td>Energy source</td>
<td>Manufactured in the body and obtained from food, distributed in body fluids</td>
</tr>
<tr>
<td><strong>Disaccharides</strong></td>
<td>Sucrose, lactose, maltose</td>
<td>Energy source</td>
<td>Sucrose is table sugar; lactose is in milk, and maltose is malt sugar; all must be broken down to monosaccharides before absorption</td>
</tr>
<tr>
<td><strong>Polysaccharides</strong></td>
<td>Glycogen</td>
<td>Storage of glucose</td>
<td>Glycogen in animal cells; other starches and cellulose are within or around plant cells</td>
</tr>
</tbody>
</table>
Lipids

**Representative Lipids in the Body**

<table>
<thead>
<tr>
<th>Lipid Type</th>
<th>Example(s)</th>
<th>Primary Function(s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatty acids</td>
<td>Lauric acid</td>
<td>Energy sources</td>
<td>Absorbed from food or synthesized in cells; transported in the blood</td>
</tr>
<tr>
<td>Glycerides</td>
<td>Monoglycerides, diglycerides, triglycerides</td>
<td>Energy sources, energy storage, insulation, and physical protection</td>
<td>Stored in fat deposits; must be broken down to fatty acids and glycerol before they can be used as an energy source</td>
</tr>
<tr>
<td>Eicosanoids</td>
<td>Prostaglandins, leukotrienes</td>
<td>Chemical messengers coordinating local cellular activities</td>
<td>Prostaglandins are produced in most body tissues</td>
</tr>
<tr>
<td>Steroids</td>
<td>Cholesterol</td>
<td>Structural components of cell membranes, hormones, digestive secretions in life</td>
<td>All steroids have the same carbon ring framework</td>
</tr>
<tr>
<td>Phospholipids, glycolipids</td>
<td>Lecithin (a phospholipid)</td>
<td>Structural components of cell membranes</td>
<td>Derived from fatty acids and nonlipid components</td>
</tr>
</tbody>
</table>

The polysaccharide glycogen, produced when multiple dehydration synthesis reactions add additional monosaccharides or disaccharides, is a carbohydrate stored in the liver and muscles. When these cells have a high demand for glucose, glycogen molecules are broken down; when the demand is low, they absorb glucose from the bloodstream and rebuild glycogen reserves.

A fatty acid, the building block of lipids, which includes a tail and a head composed of a carboxylic acid group: $-COOH$.

The carbon chain attached to the carboxylic acid group is known as the hydrocarbon tail of the fatty acid. The hydrocarbon tail is hydrophobic, so fatty acids have very limited solubility in water. In general, the length and degree of saturation, the lower the solubility of the molecule.

Three steroid molecules, which share a distinctive carbon-ring framework:

- **Cholesterol**
- **Estrogen**
- **Testosterone**
Proteins

The structural elements of amino acids, the basic units of proteins

The linkage of two amino acids by dehydration synthesis, and the breakage of peptide bonds by hydrolysis

1. Adjacent amino acids can be linked together by a covalent bond that connects the carboxyl group of one amino acid to the amino group of another.

2. Amino group
   - Central carbon
   - Carboxyl group
   - R group (variable side chain of one or more atoms)

3. Peptide bonds can also be broken through hydrolysis; the hydrolysis of a dipeptide yields a pair of amino acids.

4. The bond between amino acids is known as a peptide bond. Molecules consisting of amino acids held together by peptide bonds are called peptides. This molecule is called a dipeptide because it contains two amino acids.

Nucleic Acids - DNA and RNA

The structure of nucleotides, the subunits of a nucleic acid

The production of a linear sugar-to-phosphate-to-sugar “backbone” of a nucleic acid by dehydration synthesis
Two Classes of Nucleic Acids
- Deoxyribonucleic Acid (DNA)
- Ribonucleic Acid (RNA)

Building Block is a Nucleotide
- Sugar (Ribose or Deoxyribose)
- Phosphate Group
- Nitrogenous base

A Comparison of DNA with RNA

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>DNA</th>
<th>RNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar</td>
<td>Deoxyribose</td>
<td>Ribose</td>
</tr>
<tr>
<td>Nitrogenous bases</td>
<td>Adenine (A), guanine (G), cytosine (C), thymine (T)</td>
<td>Adenine, guanine, cytosine, uracil (U)</td>
</tr>
<tr>
<td>Number of nucleotides in typical molecule</td>
<td>Always more than 45 million</td>
<td>Varies from fewer than 100 to about 50,000</td>
</tr>
<tr>
<td>Shape of molecule</td>
<td>Paired strands coiled in a double helix</td>
<td>Varies with hydrogen bonding along the length of the strand of each of the three main types of RNA, mRNA, tRNA</td>
</tr>
<tr>
<td>Function</td>
<td>Stores genetic information that controls protein synthesis</td>
<td>Performs protein synthesis as directed by DNA</td>
</tr>
</tbody>
</table>

Adenosine triphosphate (ATP)

The reversible reaction by which ATP is formed from ADP

\[
\text{ADP} + \text{ENERGY} + P \rightleftharpoons \text{ATP}
\]
Adenosine triphosphate (ATP)

Adenosine diphosphate (ADP)

Adenosine monophosphate (AMP)

The formation of ATP begins with adenosine, an organic molecule consisting of a small ring-shaped organic molecule (adenine) and a single sugar (ribose). As adenosine molecules come together with single phosphate groups, the result is adenosine monophosphate (AMP).

Adding a second phosphate results in the formation of a high-energy bond, and it produces adenosine diphosphate (ADP).

Adding a third phosphate results in the formation of a high-energy bond, and it produces adenosine triphosphate (ATP).

**Additional energy must be provided to break the third phosphate and create adenosine triphosphate (ATP).**

---

**SUMMARY TABLE 3-9**

<table>
<thead>
<tr>
<th>Class</th>
<th>Building Blocks</th>
<th>Sources</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INORGANIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water (pp. 41-44)</td>
<td>Hydrogen and oxygen atoms</td>
<td>Solvent and transport medium for dissolved materials and heat; cooling through evaporation; medium for chemical reactions; reactant in hydrolysis.</td>
<td></td>
</tr>
<tr>
<td>Acids, bases, salts (pp. 46-47)</td>
<td>H⁺, OH⁻, various ions, and cations</td>
<td>Obtained from the diet or generated by metabolism. Structural components, buffers, source of ions.</td>
<td></td>
</tr>
<tr>
<td>Dissolved gases (pp. 41)</td>
<td>O, N₂, N₂O, and other gases</td>
<td>Atmosphere</td>
<td>O₂ required for cellular metabolism. CO₂ generated by cells as a waste product. N₂, chemical messenger involved in cardiovascular, nervous, and immune systems.</td>
</tr>
<tr>
<td><strong>ORGANIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbohydrates (pp. 40-41)</td>
<td>C, H, O; in some cases N; CH₂O in a 1:2:1 ratio</td>
<td>Obtained from the diet or manufactured in the body.</td>
<td>Energy source; some structural roles when attached to lipids or proteins; energy storage.</td>
</tr>
<tr>
<td>Lipids (pp. 47-51)</td>
<td>C, H, O, in some cases N or P; CH₂O in a 1:2:1 ratio</td>
<td>Obtained from the diet or manufactured in the body.</td>
<td>Energy source; energy storage; insulation; structural components; chemical messengers; protection.</td>
</tr>
<tr>
<td>Proteins (pp. 52-53)</td>
<td>C, H, O, N, commonly S</td>
<td>20 common amino acids; roughly half can be manufactured in the body, others must be obtained from the diet.</td>
<td>Catalysis for metabolic reactions; structural components; movement; transport; buffers; defense, control and coordination of activities.</td>
</tr>
<tr>
<td>Nucleic acids (pp. 52-53)</td>
<td>C, H, O, N, and P; nucleotides composed of phosphoric acid, sugars, and nitrogenous bases</td>
<td>Obtained from the diet or manufactured in the body.</td>
<td>Storage and processing of genetic information.</td>
</tr>
<tr>
<td>High-energy compounds (pp. 55-60)</td>
<td>Nucleotides joined to phosphates by high-energy bonds</td>
<td>Synthesized by all cells.</td>
<td>Storage or transfer of energy.</td>
</tr>
</tbody>
</table>