Chapter 2
The Chemical Basis of Life

PowerPoint Lectures for
Biology: Concepts & Connections, Sixth Edition
Campbell, Reece, Taylor, Simon, and Dickey

Lecture by Richard L. Myers
Introduction: Who Tends This Garden?

- Chemicals are the stuff that make up our bodies and those of other organisms
  - They make up the physical environment as well

- The ordering of atoms into molecules represents the lowest level of biological organization
  - Therefore, to understand life, it is important to understand the basic concepts of chemistry
Introduction: Who Tends This Garden?

- The Amazonian rain forest is a showcase for the diversity of life on Earth
  - An example is the lemon ant, which prevents all trees except the lemon ant tree from growing in their gardens
    - The ants inject a chemical into other trees that kills them
    - The ants live in the hollow stems of the lemon ant tree
ELEMENTS, ATOMS, AND MOLECULES
2.1 Living organisms are composed of about 25 chemical elements

- Chemicals are at the base level of biological hierarchy

- They are arranged into higher and higher levels of structural organization
  - Arrangement eventually leads to formation of living organisms
2.1 Living organisms are composed of about 25 chemical elements

- Living organisms are composed of matter, which is anything that occupies space and has mass (weight)
  - Matter is composed of chemical elements
    - Element—a substance that cannot be broken down to other substances
    - There are 92 elements in nature—only a few exist in a pure state
  - Life requires 25 essential elements; some are called trace elements
<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Percentage of Human Body Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>65.0</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>18.5</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>9.56</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
<td>3.3</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>1.5</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
<td>1.0</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>0.4</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>0.3</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>0.2</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl</td>
<td>0.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trace elements (less than 0.01%): boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2 CONNECTION: Trace elements are common additives to food and water

- Some trace elements are required to prevent disease
  - Without iron, your body cannot transport oxygen
  - An iodine deficiency prevents production of thyroid hormones, resulting in goiter
2.2 CONNECTION: Trace elements are common additives to food and water

- Several chemicals are added to food for a variety of reasons
  - Help preserve it
  - Make it more nutritious
  - Make it look better

- Check out the “Nutrition Facts” label on foods and drinks you purchase
2.3 Elements can combine to form compounds

- **Compound**—a substance consisting of two or more different elements combined in a fixed ratio
  - There are many compounds that consist of only two elements
    - Table salt (sodium chloride or NaCl) is an example
    - Sodium is a metal, and chloride is a poisonous gas
    - However, when chemically combined, an edible compound emerges
Sodium + Chlorine → Sodium Chloride
Chlorine
Sodium Chloride
Many of the compounds in living organisms contain carbon, hydrogen, oxygen, and nitrogen

- DNA, for example, contains all four of these elements

Interestingly, different arrangements of elements provide unique properties for each compound
2.4 Atoms consist of protons, neutrons, and electrons

- An **atom** is the smallest unit of matter that still retains the properties of an element.
  - Atoms are made of over a hundred subatomic particles, but only three are important for biological compounds:
    - **Proton**—has a single positive electrical charge
    - **Electron**—has a single negative electrical charge
    - **Neutron**—is electrically neutral
2.4 Atoms consist of protons, neutrons, and electrons

- Elements differ in their number of protons, neutrons, and electrons
- Helium has two protons, two neutrons, and two electrons
- Carbon has six protons, six neutrons, and six electrons
Electron cloud

Nucleus

2e电子

电子

质子=4

中子=2

电子

2个质子

2个中子

质子数=4

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2.4 Atoms consist of protons, neutrons, and electrons

- Neutrons and protons are packed in the atom’s nucleus
  - The negative charge of electrons and the positive charge of protons keep electrons near the nucleus
  - The number of protons is the atom’s atomic number
    - Carbon with 6 protons has an atomic number of 6
    - The mass number is the sum of the protons and neutrons in the nucleus (carbon-12 is written $^{12}\text{C}$)
Electron cloud

Nucleus

6 \text{ Protons}

6 \text{ Neutrons}

6 \text{ Electrons}

\text{Mass number} = 12
2.4 Atoms consist of protons, neutrons, and electrons

- Although all atoms of an element have the same atomic number, some differ in mass number
  - The variations are **isotopes**, which have the same numbers of protons and electrons but different numbers of neutrons
    - One isotope of carbon has 8 neutrons instead of 6 (written $^{14}\text{C}$)
    - Unlike $^{12}\text{C}$, $^{14}\text{C}$ is an unstable (radioactive) isotope that gives off energy
<table>
<thead>
<tr>
<th></th>
<th>Carbon-12</th>
<th>Carbon-13</th>
<th>Carbon-14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Neutrons</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Electrons</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
2.5 CONNECTION: Radioactive isotopes can help or harm us

- Living cells cannot distinguish between isotopes of the same element
  - Therefore, when radioactive compounds are used in metabolic processes, they act as tracers
  - Radioactivity can be detected by instruments

- With instruments, the fate of radioactive tracers can be monitored in living organisms
2.5 CONNECTION: Radioactive isotopes can help or harm us

- Biologists use radioactive tracers in research
  - Radioactive $^{14}\text{C}$ was used to show the route of $^{14}\text{CO}_2$ in formation of sugar during plant photosynthesis
2.5 CONNECTION: Radioactive isotopes can help or harm us

- Radioactive tracers are frequently used in medical diagnosis

- Sophisticated imaging instruments are used to detect them
  - An imaging instrument that uses positron-emission tomography (PET) detects the location of injected radioactive materials
  - PET is useful for diagnosing heart disorders and cancer and in brain research
Healthy brain

Alzheimer’s patient
2.5 CONNECTION: Radioactive isotopes can help or harm us

- In addition to benefits, there are also dangers associated with using radioactive substances
  - Uncontrolled exposure can cause damage to some molecules in a living cell, especially DNA
  - Chemical bonds are broken by the emitted energy, which causes abnormal bonds to form
2.6 Electron arrangement determines the chemical properties of an atom

- Only electrons are involved in chemical activity
- Electrons occur in energy levels called electron shells
  - Information about the distribution of electrons is found in the *periodic table of the elements*
2.6 Electron arrangement determines the chemical properties of an atom

- An atom may have one, two, or three electron shells
  - The number of electrons in the outermost shell determines the chemical properties of the atom
  - The first shell is full with two electrons, whereas the second and third will hold up to eight electrons
2.6 Electron arrangement determines the chemical properties of an atom

- Atoms want to fill their outer electron shells
  - To accomplish this, the atom can share, donate, or receive electrons
  - This results in attractions between atoms called chemical bonds
2.7 Ionic bonds are attractions between ions of opposite charge

- An ion is an atom or molecule with an electrical charge resulting from gain or loss of electrons
  - When an electron is lost, a positive charge results; when one is gained, a negative charge results

- Two ions with opposite charges attract each other
  - When the attraction holds the ions together, it is called an ionic bond
Transfer of electron

Na  Sodium atom

Cl  Chlorine atom
Transfer of electron

Na
Sodium atom

Cl
Chlorine atom

Na⁺
Sodium ion

Cl⁻
Chloride ion

Sodium chloride (NaCl)
2.8 Covalent bonds join atoms into molecules through electron sharing

- A **covalent bond** results when atoms share outer-shell electrons
  - A **molecule** is formed when atoms are held together by covalent bonds
<table>
<thead>
<tr>
<th>Molecular Formula</th>
<th>Electron-Distribution Diagram</th>
<th>Structural Formula</th>
<th>Space-Filling Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2$</td>
<td>![H2 Diagram]</td>
<td>H–H</td>
<td>![H2 Model]</td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>![O2 Diagram]</td>
<td>$\text{O}–\text{O}$</td>
<td>![O2 Model]</td>
</tr>
<tr>
<td>$\text{CH}_4$ Methane</td>
<td>![CH4 Diagram]</td>
<td>H–C–H</td>
<td>![CH4 Model]</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$ Water</td>
<td>![H2O Diagram]</td>
<td>O–H</td>
<td>![H2O Model]</td>
</tr>
</tbody>
</table>
### Table 2.8: Alternative Ways to Represent Four Common Molecules

<table>
<thead>
<tr>
<th>Molecular Formula</th>
<th>Electron-Distribution Diagram</th>
<th>Structural Formula</th>
<th>Space-Filling Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2$</td>
<td>![H2 Diagram]</td>
<td>$\text{H} \equiv \text{H}$</td>
<td>![H2 Model]</td>
</tr>
<tr>
<td></td>
<td>![Single bond]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>![O2 Diagram]</td>
<td>$\text{O} \equiv \text{O}$</td>
<td>![O2 Model]</td>
</tr>
<tr>
<td></td>
<td>![Double bond]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecular Formula</td>
<td>Electron-Distribution Diagram</td>
<td>Structural Formula</td>
<td>Space-Filling Model</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------------</td>
<td>--------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>CH₄ Methane</td>
<td>![CH₄ Diagram]</td>
<td>H–C–H</td>
<td>![CH₄ Model]</td>
</tr>
<tr>
<td>H₂O Water</td>
<td>![H₂O Diagram]</td>
<td>O–H</td>
<td>![H₂O Model]</td>
</tr>
</tbody>
</table>
2.9 Unequal electron sharing creates polar molecules

- Atoms in a covalently bonded molecule continually compete for shared electrons
  - The attraction (pull) for shared electrons is called **electronegativity**
  - More electronegative atoms pull harder
Unequal electron sharing creates polar molecules

- In molecules of only one element, the pull toward each atom is equal, because each atom has the same electronegativity
  - The bonds formed are called **nonpolar covalent bonds**
2.9 Unequal electron sharing creates polar molecules

- Water has atoms with different electronegativities
  - Oxygen attracts the shared electrons more strongly than hydrogen
  - So, the shared electrons spend more time near oxygen
  - The result is a **polar covalent bond**
2.9 Unequal electron sharing creates polar molecules

- In H$_2$O the oxygen atom has a slight negative charge and the hydrogens have a slight positive charge
  - Molecules with this unequal distribution of charges are called **polar molecules**
2.10 Hydrogen bonds are weak bonds important in the chemistry of life

- Some chemical bonds are weaker than covalent bonds

- Hydrogen, as part of a polar covalent bond, will share attractions with other electronegative atoms
  - Examples are oxygen and nitrogen

- Water molecules are electrically attracted to oppositely charged regions on neighboring molecules
  - Because the positively charged region is always a hydrogen atom, the bond is called a hydrogen bond
Hydrogen bond
Hydrogen bonding causes molecules to stick together, a property called **cohesion**

- Cohesion is much stronger for water than other liquids
- This is useful in plants that depend upon cohesion to help transport water and nutrients up the plant.
2.11 Hydrogen bonds make liquid water cohesive

- Cohesion is related to **surface tension**—a measure of how difficult it is to break the surface of a liquid
  
  - Hydrogen bonds are responsible for surface tension
Water-conducting cells

Adhesion

Cohesion

Direction of water movement

Water movement in plants is facilitated by two primary forces: adhesion and cohesion. Adhesion refers to the attraction between water molecules and the walls of the water-conducting cells. Cohesion, on the other hand, is the attractive force between adjacent water molecules due to hydrogen bonding.

The diagram illustrates the upward movement of water in a tree, facilitated by these forces.

Scale: 150 µm
2.12 Water’s hydrogen bonds moderate temperature

- Because of hydrogen bonding, water has a greater ability to resist temperature change than other liquids
  - **Heat** is the energy associated with movement of atoms and molecules in matter
  - **Temperature** measures the intensity of heat
- Heat must be absorbed to break hydrogen bonds; heat is released when hydrogen bonds form
2.13 Ice is less dense than liquid water

- Water can exist as a gas, liquid, and solid
  - Water is less dense as a solid, a property due to hydrogen bonding
2.13 Ice is less dense than liquid water

- When water freezes, each molecule forms a stable hydrogen bond with four neighbors
  - A three-dimensional crystal results
  - There is space between the water molecules
- Ice is less dense than water, so it floats
Liquid water

Hydrogen bonds constantly break and re-form

Ice

Hydrogen bonds are stable

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2.14 Water is the solvent of life

- A **solution** is a liquid consisting of a uniform mixture of two or more substances
  - The dissolving agent is the **solvent**
  - The substance that is dissolved is the **solute**
2.14 Water is the solvent of life

- Water is a versatile solvent that is fundamental to life processes
  - Its versatility results from its polarity
  - Table salt is an example of a solute that will go into solution in water
    - Sodium and chloride ions and water are attracted to each other because of their charges
Ion in solution

Salt crystal
2.15 The chemistry of life is sensitive to acidic and basic conditions

- A few water molecules can break apart into ions
  - Some are hydrogen ions (H\(^+\))
  - Some are hydroxide ions (OH\(^-\))
    - Both are extremely reactive
    - A balance between the two is critical for chemical processes to occur in a living organism
Chemicals other than water can contribute $\text{H}^+$ to a solution

- They are called **acids**

- An example is hydrochloric acid (HCl)
  - This is the acid in your stomach that aids in digestion

An acidic solution has a higher concentration of $\text{H}^+$ than $\text{OH}^-$
2.15 The chemistry of life is sensitive to acidic and basic conditions

- Some chemicals accept hydrogen ions and remove them from solution
  - These chemicals are called bases
  - For example, sodium hydroxide (NaOH) provides OH\(^-\) that combines with H\(^+\) to produce H\(_2\)O (water)
  - This reduces the H\(^+\) concentration
2.15 The chemistry of life is sensitive to acidic and basic conditions

- A **pH scale** (pH = potential of hydrogen) is used to describe whether a solution is acidic or basic
  - pH ranges from 0 (most acidic) to 14 (most basic)
  - A solution that is neither acidic or basic is neutral (pH = 7)
Acidic solutions:
- Battery acid
- Lemon juice, gastric juice
- Grapefruit juice, soft drink, vinegar, beer
- Tomato juice
- Rain water
- Human urine
- Saliva
- Pure water
- Human blood, tears
- Seawater
- Milk of magnesia
- Household ammonia
- Household bleach
- Oven cleaner

Neutral solutions:
- NEUTRAL
- [H^+] = [OH^-]

Increasingly acidic (higher concentration of H^+):
- 0
- 1
- 2
- 3
- 4

Increasingly basic (lower concentration of H^+):
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
Acidic solution

Neutral solution

Basic solution
2.16 CONNECTION: Acid precipitation and ocean acidification threaten the environment

- When we burn fossil fuels (gasoline and heating oil), air-polluting compounds and CO$_2$ are released into the atmosphere
  - Sulfur and nitrous oxides react with water in the air to form acids
    - These fall to Earth as acid precipitation, which is rain, snow, or fog with a pH lower than 5.6
  - Additional CO$_2$ in the atmosphere contributes to the “greenhouse” effect and alters ocean chemistry
An important question is, has life evolved elsewhere?
  - Water is necessary for life as we know it

The National Aeronautics and Space Administration (NASA) has evidence that water was once abundant on Mars
  - Scientists have proposed that reservoirs of water beneath the surface of Mars could harbor microbial life
August 1999

September 2005

New deposit
CHEMICAL REACTIONS
2.18 Chemical reactions make and break bonds, changing the composition of matter

- You learned that the structure of atoms and molecules determines the way they behave
  - Remember that atoms combine to form molecules
  - Hydrogen and oxygen can react to form water

\[ 2H_2 + O_2 \rightarrow 2H_2O \]
2.18 Chemical reactions make and break bonds, changing the composition of matter

- The formation of water from hydrogen and oxygen is an example of a chemical reaction.

- The reactants (H\(_2\) and O\(_2\)) are converted to H\(_2\)O, the product.
  - Organisms do not make water, but they do carry out a large number of chemical reactions that rearrange matter.
  - Photosynthesis is an example where plants drive a sequence of chemical reactions that produce glucose.
2 H₂ + O₂ → 2 H₂O
Electron transfer between atoms creates electron sharing between atoms creates Chemical Bonds.

Atomic number of each element number present equals atomic number of each element number may differ in number in outer shell determines formation of ions.

Electron transfer between atoms creates unequal sharing creates equal sharing creates nonpolar covalent bonds.

Attraction between ions creates unequal sharing creates equal sharing creates nonpolar covalent bonds.

Example is water has important qualities due to polarity and

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Atoms have positively charged, have neutral, and have negatively charged.

(a) number present equals atomic number of each element

(b) number may differ in

(c) number in outer shell determines formation of

(d)
Electron transfer between atoms creates electron sharing between atoms creates chemical bonds.

- **Ions**
  - Attraction between ions creates.
  - Unequal sharing creates.
- **Nonpolar covalent bonds**
  - Equal sharing creates.

Example is water, which has important qualities due to polarity and...
Fluorine atom

Potassium atom
You should now be able to

1. Describe the importance of chemical elements to living organisms
2. Explain the formation of compounds
3. Describe the structure of an atom
4. Distinguish between ionic, hydrogen, and covalent bonds
5. List and define the life-supporting properties of water
6. Explain the pH scale and the formation of acid and base solutions
7. Define a chemical reaction and explain how it changes the composition of matter