2

LIFE'S CHEMICAL BASIS

Chapter Outline

Learning Objectives

2.1 Describe a few properties of atoms and elements.

2.1.1 What is an atom composed of?
2.1.2 What is an element?
2.1.3 Describe how atoms are arranged in the periodic table.
2.1.4 What are isotopes?
2.1.5 Explain how radioisotopes can help scientists to measure the age of a fossil.
2.1.6 How are radioisotopes used as tracers to study biological processes?

2.2 Describe the arrangement of electrons in atoms.

2.2.1 Explain how electrons are organized in orbitals.
2.2.2 Explain the shell model of electrons with an example.
2.2.3 Why do some elements occur in nature as solitary atoms?
2.2.4 Why are atoms with vacancies said to be chemically reactive?
2.2.5 Define free radicals and explain why they are dangerous to life.
2.2.6 How do atoms become ions?

2.3 Describe the different types of chemical bonds.

2.3.1 Define a chemical bond.
2.3.2 With the help of suitable examples, distinguish between ionic and covalent bonds.
2.3.3 Define polarity and explain why ionic bonds are extremely polar.
2.3.4 What is electronegativity and what does it depend on?
2.3.5 Describe how covalent bonds between atoms are represented.
2.3.6 Distinguish between polar and nonpolar covalent bonds with examples.

2.4 Describe the properties that liquid water acquires due to hydrogen bonding.

2.4.1 Draw the hydrogen bond between two water molecules.
2.4.2 Describe the nature of a hydrogen bond.
2.4.3 Why is water a good solvent?
2.4.4 Describe the mechanism by which different kinds of substances dissolve in water.
2.4.5 Distinguish between hydrophilic and hydrophobic substances.
2.4.6 Why do oils not mix with water?
2.4.7 Why does evaporation cause cooling?
2.4.8 Explain how the movement of water molecules varies with temperature.

2.5 Describe the importance of maintaining the pH of a biological system.

2.5.1 What is pH?

2.5.2 Differentiate between acids and bases.
2.5.3 Differentiate between strong acids and weak acids with examples.
2.5.4 Explain how buffers maintain the pH of solutions.
2.5.6 Explain why it is important to maintain the pH of biological systems within a consistent range.

2.6 Describe the consequences of exposure to methylmercury.
2.6.1 How do humans get exposed to methylmercury?
2.6.2 What are the harmful health effects of methylmercury consumption?

Key Concepts and Terms

1. **Key Concept: Atoms and Elements**
   Atoms, the building blocks of all matter, differ in their numbers of protons, neutrons, and electrons. Atoms of an element have the same number of protons.

   Take-Home Message 2.1
   All matter consists of atoms, tiny particles that in turn consist of electrons moving around a nucleus of protons and neutrons. An element is a pure substance that consists only of atoms with the same number of protons. Isotopes are forms of an element that have different numbers of neutrons. Unstable nuclei of radioisotopes break down spontaneously (decay) at a predictable rate to form predictable products.

   Key Terms
   - **atomic number** Number of protons in the atomic nucleus; determines the element.
   - **charge** Electrical property. Opposite charges attract, and like charges repel.
   - **electron** Negatively charged subatomic particle.
   - **element** A pure substance that consists only of atoms with the same number of protons.
   - **isotopes** Forms of an element that differ in the number of neutrons their atoms carry.
   - **mass number** Of an isotope, the total number of protons and neutrons in the atomic nucleus.
   - **neutron** Uncharged subatomic particle in the atomic nucleus.
   - **nucleus** Core of an atom; occupied by protons and neutrons.
   - **periodic table** Tabular arrangement of all known elements by their atomic number.

- **proton** Positively charged subatomic particle that occurs in the nucleus of all atoms.
- **radioactive decay** Process by which atoms of a radioisotope emit energy and/or subatomic particles when their nucleus spontaneously breaks up.
- **radioisotope** Isotope with an unstable nucleus.
- **tracer** A molecule with a detectable component.

2. **Key Concept: Why Electrons Matter**

Whether and how an atom interacts with other atoms depends on the number of electrons it has. An atom with an unequal number of electrons and protons is an ion.

Take-Home Message 2.2

An atom's electrons are the basis of its chemical behavior. Shells represent all electron orbitals at one energy level in an atom. When the outermost shell is not full of electrons, the atom has a vacancy. Atoms with vacancies tend to interact with other atoms.

Key Terms

- **free radical** Atom with an unpaired electron.
- **ion** Charged atom.
- **shell model** Model of electron distribution in an atom.

3. **Key Concept: Atoms Bond**

Atoms of many elements interact by acquiring, sharing, and giving up electrons. Interacting atoms may form ionic, covalent, or hydrogen bonds.

Take-Home Message 2.3

A chemical bond forms between atoms when their electrons interact. A chemical bond may be ionic or covalent depending on the atoms taking part in it. An ionic bond is a strong mutual attraction between two ions of opposite charge. Ionic bonds are very polar. Atoms share a pair of electrons in a covalent bond. When the atoms share electrons unequally, the bond is polar.

Key Terms

- **chemical bond** An attractive force that arises between two atoms when their electrons interact.
- **compound** Molecule that has atoms of more than one element.
- **covalent bond** Chemical bond in which two atoms share a pair of electrons.
- **electronegativity** Measure of the ability of an atom to pull electrons away from other atoms.

- **ionic bond** Type of chemical bond in which a strong mutual attraction links ions of opposite charge.
- **polarity** Separation of charge into positive and negative regions.

4. **Key Concept: Water**

Hydrogen bonding among individual molecules gives water properties that make life possible: temperature stabilization, cohesion, and the ability to dissolve many other substances.

Take-Home Message 2.4

Extensive hydrogen bonding among water molecules, which arises from the polarity of the individual molecules, gives water special properties. Liquid water is an excellent solvent. Hydrophilic substances such as salts and sugars dissolve easily in water to form solutions. Hydrophobic substances do not dissolve in water. Water also has cohesion, and it stabilizes temperature.

Key Terms

- **cohesion** Property of a substance that arises from the tendency of its molecules to resist separating from one another.
- **evaporation** Transition of a liquid to a vapor.
- **hydrogen bond** Attraction between a covalently bonded hydrogen atom and another atom taking part in a separate covalent bond.
- **hydrophilic** Describes a substance that dissolves easily in water.
- **hydrophobic** Describes a substance that resists dissolving in water.
- **salt** Compound that releases ions other than H^+ and OH^- when it dissolves in water.
- **solute** A dissolved substance.
- **solution** Uniform mixture of solute completely dissolved in solvent.
- **solvent** Liquid that can dissolve other substances.
- **temperature** Measure of molecular motion.

5. **Key Concept: Hydrogen Power**

Most of the chemistry of life occurs in a narrow range of pH, so most fluids inside organisms are buffered to stay within that range.

Take-Home Message 2.5

The number of hydrogen ions in a fluid determines its pH. Most biological systems function properly only within a narrow range of pH. Acids release hydrogen ions in water; bases accept them. Salts release ions other than H^+ and OH^-. Buffers help keep pH stable. Inside organisms, they are part of homeostasis.

Key Terms

- **acid** Substance that releases hydrogen ions in water.
- **base** Substance that accepts hydrogen ions in water.
- **buffer** Set of chemicals that can keep the pH of a solution stable by
- alternately donating and accepting ions that contribute to pH.
- **concentration** Amount of solute per unit volume of solution.
- **pH** Measure of the number of hydrogen ions in a fluid.

Links to Earlier Concepts

In this chapter, you will explore the first level of life's organization—atoms—as you encounter the first example of how the same building blocks, arranged different ways, form different products (Section 1.1). You will also see one aspect of homeostasis, the process by which organisms keep themselves in a state that favors cell survival (1.2).

Suggestions for Presenting the Material

- First and foremost, keep in mind that the abstract nature of chemistry and the associated terminology are tremendous obstacles to learning. This is highly intimidating—especially to nonscience majors. While the chapter materials are considered elementary and certainly critical to the topic of biology, care must be taken in developing a well grounded presentation. As this topic most often comes early in the semester, take care to ensure students are not overly discouraged if they struggle.
- The extensive use of examples of common chemical compounds and their properties will help provide context.
- Use common examples and references highlighted throughout the text, for example, isotopes, electron excitation, bonding, buffers, and water, to stress the importance of reading.
- Use and have students reference in class the numerous diagrams and illustrations in the text.
- Use ball-and-stick models (see the Enrichment section below) to illustrate concepts in this chapter. Larger examples can be made using inexpensive materials like tennis balls and dowels. This is especially effective when illustrating properties of polar molecules in a large lecture hall.
- Stress the foundational nature of the chapter material and its importance to the field of biology.

- Show Figure 2.5, which uses the example of table salt (NaCl) to illustrate the concept of ionic bonds. Refer students back to this as a review tool.
- Figure 2.9 provides an excellent reference for explaining acid, base, and pH scales. Note in particular the pH values of common household products. Emphasize that acids and bases are not necessarily terms that describe *corrosive* substances!
- The properties of water are important to life on Earth. Describe the polarity of water molecules; then proceed to the influence that water molecules have on cells and cellular environments.
- **Common Student Misconceptions:**
    - Students misunderstand and get confused when discussing atomic structures. Quiz students on the basic terms to encourage them to commit these to memory.

Classroom and Laboratory Enrichment

- Students are often intimidated by chemistry, especially if they lack sufficient high school background in this area, or if they have been out of school for several years. The more you ground your presentations using everyday examples, the more comfortable your students will be. When possible, emphasize the biological significance of chemistry. Give students frequent opportunities to use new terms. Use illustrations or diagrams, pause often, and interject questions to gauge their level of understanding.
- Most undergraduates have trouble visualizing abstract items such as atoms and molecules. To help them visualize atoms and molecules, use ball-and-stick models that are very large and easy to see. Models help students understand the size relationships among molecules. Overhead transparencies of ball-and-stick models are especially useful when covering the larger carbon compounds.
- Reinforce chemical bonding patterns through the use of common examples. Present sketches or illustrations of each type. Use a pair-share activity to have students identify chemical bonding types with classmates.
- Simple ball-and-stick models are also useful for demonstrating the hydrogen bonding that occurs between water molecules and the latticework structure of ice.
- Fill a large jar with water, then add salad oil. Shake the bottle, then allow it to sit on the front desk. Ask students to explain what has happened. Add a few drops of methylene blue (a polar dye) and sudan III fat stain (a nonpolar dye) to the jar and shake. Students will see that the water layer is blue and the oil layer is red; ask them to speculate about how this occurs.

- Draw a pH scale on the board (or display Figure 2.14), and discuss pH values of familiar substances. Use examples of pH in nature, their own bodies, or food.
- If your class is small, demonstrate the use of a pH meter. For larger groups or in lab, pH paper can be used to give each student a chance to quickly determine the pH of sample solutions.
- If you are teaching in a room with a periodic table of the elements hanging on the wall, point out the major elements, or use an overhead transparency to show the same items. Relate subatomic particles with the atomic number and mass.
- Prepare a glass of iced tea (instant mix) with added sugar and lemon. Which ingredients are compounds? What are the components of the mixture?
- Bring a package of buffered and regular aspirin to class. Ask students to investigate the difference(s) in ingredients.
- Using the names of the active ingredients on an antacid package, explain how they act as *buffers* to stomach acid.

Application: Mercury Rising

- What body systems does mercury most impact?
- Why is mercury so harmful to the developing brain?
- What are the differences between mercury and methylmercury?
- Other than tuna, what are other dietary sources of mercury?
- Have students estimate how much mercury they consume by analyzing their diet.

Additional Ideas for Classroom Discussion

- Show diagrams of subatomic particles, atoms, and molecules to student groups. Have them identify these along with their properties.
- Have students form into small groups and discuss chemical bonding types. One at a time, call on individual groups and have them explain one type to the whole class.
- Show a copy of a soft drink ingredient label to the class. Have them explain why soft drinks have such a low pH. What ingredient is responsible for this low pH?

- What is acid precipitation? What chemical reaction is responsible for the mildly acidic pH of normal rainwater? What chemicals are responsible for acid precipitation?
- Discuss with the class why water is so critical to life. Assess student understanding of the properties of water by using an open-ended question-and-answer format. For example, what is meant by water being the "universal solvent" for Earth?
- What would happen to fish and other aquatic organisms in temperate climates if water sank when it froze instead of floated?
- What is the difference between the composition of a molecule of a substance and an atom of that substance?
- If atoms are beyond the reach of visualization even by electron microscopes, how do we know so much about their structure?
- Some pain relievers are advertised as "tribuffered." What is meant by this statement? Do you think this is an important advantage or just a sales gimmick?
- Television commercials portray the "acid stomach" as needing immediate R-O-L-A-I-D-S. Is the stomach *normally* acidic? Have students find the pH of stomach acids (gastric fluids) on the chart Figure 2.9. How do you know when there is too much acid in the system?

How Would You Vote? Classroom Discussion Ideas

- Monitor the voting for an online question. Ask students to justify their answer, considering topics such as corporate responsibility, consumer education, and relative risk.
- Have students investigate other chemical contaminants in food, and how these are handled by different manufacturers.

Term Paper Topics, Library Activities, and Special Projects

- Have students investigate and prepare a short paper on common elements used in food additives for humans, livestock, or plant fertilizers.
- Why are the cells lining the stomach able to withstand pH ranges between one and three?
- Have students investigate and explain the functional relationship between acids and bases. What are the homeostatic mechanisms that help the human body regulate blood pH? Also, how does the body measure blood pH?

- Discuss strategies currently being considered by the United States and other nations to remedy acid rain. What suggestions would you make to help solve this problem?
- Describe some of the roles played by ions in the human body.
- Many elements have radioactive isotopes that are useful as tracers in biological systems. Show how $^{14}CO_2$ can be used to follow the fate of carbon as it is incorporated into carbohydrate.
- The structure of atoms can be deduced using nuclear magnetic resonance (NMR) and mass spectrometer machines. Have students prepare a short report on each of these instruments.
- Using a pH meter or test paper, examine the degree of acidity/alkalinity of common household products. If the substance is not a liquid, mix it with water according to package directions before testing.
- Most of the content of human blood is water. However, synthetic blood has been made and tested. What is the base in this fluid? Is it a feasible substitute? Report on its advantages and disadvantages.

Responses to *Data Analysis Activities*

1. The PET scan shown in Figure 2.11 monitors MAO-B activity, low levels of which are associated with impulsiveness and other behavioral problems. The smoker shows lower MAO-B activity than the non-smoker, suggesting that the diminished MAO-B activity may have contributed to the smoker's inclination to smoke despite knowledge of its harmful effects.
2. An alternate interpretation of the data presented in Figure 2.11 is that smoking leads to the reduced activity of MAO-B.
3. An appropriate control for this study, if ethically appropriate, would be to monitor the same person before and after they smoke to determine the immediate effects of smoking on MAO-B activity.

Possible Responses to *Critical Thinking* Questions

1. Medieval alchemists understood the transformative processes of heat and other simple chemical reactions but lacked a fundamental understanding of matter at the atomic level. Specifically, they were attempting to remove protons from lead (Pb) to create gold (Au), a process that would be incredibly difficult and require massive quantities of energy as lead represents a particularly stable element.

2. Lithium is an alkali metal that has a single valence electron. It easily gives up the valence electron to form a cation (has a positive charge).

3. If 210Po emits an alpha particle, it is losing two protons. Given that Po contains 82 protons, an investigation of the periodic table finds that the element with two less protons is Pb (lead).

4. Rewrite: Lab workers are told to wipe off splashes with a towel before washing as in undiluted form; the acid may not cause appreciable damage to the exposed surface. However, exposure to water can increase the corrosive nature of the acid to the point where it will significantly degrade the surface to which it is exposed.