# CHAPTER 2: THE CHEMICAL BASIS OF LIFE I: ATOMS, MOLECULES, AND WATER

## WHERE DOES IT ALL FIT IN?

Chapter 2 investigates the fundamental principles of chemistry making up the first hierarchy of living systems. It can be an overwhelming chapter because of the diversity of concepts needed to build an understanding of biological molecules and their molecular environment. Reinforce to students that the chemistry being covered in this chapter is essential for understanding cell structure and organismal function, and principles of homeostasis being taught during the semester. Regularly refer to Chapter 2 when discussing the topics that rely on knowledge of molecules and the properties of water.

## SYNOPSIS

A basic understanding of chemistry is necessary to the study of biology because the two are inexorably intertwined. Living organisms are chemical machines composed of molecules that continually undergo chemical reactions to become new molecules.

Atoms are composed of protons, neutrons, and electrons. Each subatomic particle has its effect on the chemical identity and interactivity of each element with all other elements. Formation of molecules from elements depends primarily on the tendency of electrons to occur in pairs, balance positive and negative charges, and fill their outermost shell. Chemical bonds result from trading or sharing electrons; shared bonds are stronger because they require the continued close proximity of atoms to one another.

Water, a simple but elegant molecule, predominates in living organisms and is unique in the life-giving characteristics stemming from its polar nature. Water clings to other polar molecules (adhesion), as well as itself (cohesion), by forming transient hydrogen bonds. These bonds absorb thermal energy; consequently the presence of water has a moderating effect on temperature changes. It is also a powerful solvent for other polar molecules and excludes nonpolar molecules, enabling the formation of biological membranes.

 

## COMMON STUDENT MISCONCEPTIONS

There is ample evidence in the educational literature that student misconceptions of information will inhibit the learning of concepts related to the misinformation. The following concepts covered in Chapter 2 are commonly the subject of student misconceptions. This information on "bioliteracy" was collected from faculty and the science education literature.

- Students believe that mass and volume both describe the amount of matter.
- Students believe that mass and weight are the same and they are equal at all times.
- Students believe that the density of an object depends only on its volume.
- Students believe that the temperature of an object drops when it freezes.
- Students believe that particles of solids exhibit no motion.
- Students believe that atoms can be seen with a standard microscope.
- Students believe that the terms atoms and elements are synonymous.
- Students believe that the atomic nucleus is large and in close proximity to the orbitals.
- Students believe that atoms have electrons circling them like planets around the sun.
- Students believe that the electron shell is there to protect the nucleus.
- Students believe that elements of solids are hard, whereas elements of gases are soft.
- Students believe that gas molecules weigh less than solid molecules.
- Students believe that atomic mass values are affected by electron number.
- Students believe that molecules are glued together.
- Students believe that all bonds store and release energy.
- Students believe that the chemical bond is a physical thing made of matter.
- Students believe that ionic compounds form neutral molecules such as $Na^+Cl^-$ in water.
- Students believe that electrons in covalent bonds belong to the particular atom they came from.
- Students believe that electron pairs are equally shared in all covalent bonds.
- Students believe that the strength of acids and bases is the same thing as its concentration.
- Students believe that substances containing H are acidic; substances containing OH are basic.
- Students believe that when a proton donor acid reacts, the nucleus of an atom loses a proton.
- Students believe that the pH scale represents a linear change in measurement.
- Students believe that buffers make a solution neutral.
- Students believe that all acids and bases are harmful and poisonous.
- Students believe that salts don't have a pH value.
- Students believe that pH is a measure of acidity.

 

**INSTRUCTIONAL STRATEGY PRESENTATION ASSISTANCE**

This is the material that many prospective biology students abhor. After all, if they enjoyed this type of information they would be taking chemistry as an elective, not biology. Although most programs consider basic high school chemistry a prerequisite to introductory biology, fewer high schools offer such a course now than did ten years ago. As a result, part of the class will be bored if you get too basic and the other part of the class will be lost if you assume this chapter is a review. Try to find a happy medium. A short pretest on the material may help gauge the level of your students, and may surprise some who thought they knew the material.

Many students have a math phobia as well as a chemistry phobia and have a difficult time with anything that has equations, plus, minus, and equal signs. pH is a difficult concept partly because of the invention of calculators; logarithms are ancient history. Stress that each number on the pH scale is different from its nearest neighbor by a factor of ten, like the Richter scale for earthquakes and the decibel scale for sound. Oxidation/reduction reactions cause problems as well; remember that reduced compounds add electrons and oxidized compounds lose electrons. This is one time that being reduced results in a gain!

 

## HIGHER LEVEL ASSESSMENT

Higher level assessment measures a student's ability to use terms and concepts learned from the lecture and the textbook. A complete understanding of biology content provides students with the tools to synthesize new hypotheses and knowledge using the facts they have learned. The following table provides examples of assessing a student's ability to apply, analyze, synthesize, and evaluate information from Chapter 2.

| | |
|---|---|
| **Application** | • Have students apply the concepts of adhesion and cohesion of water to properties of glue. (2.3, 2.4)<br>• Ask students to explain why the digestive systems of animals must be adapted to break down covalent bonds yet there is no particular system for breaking down ionic bonds. (2.2)<br>• Ask students to explain why pH is a factor used in food preservation.(2.4) |
| **Analysis** | • Ask students to explain what types of organisms would be most affected if their bodies took in an abundance of isotopes having a higher atomic mass. (2.1)<br>• Ask students to select and analyze the three characteristics of water that would help an organism survive in the desert. (2.4)<br>• Have the students explain why the "static cling" of dry clothing can be removed simply by spraying a mist of water on the clothing. (2.2) |
| **Synthesis** | • Ask students to describe how an organism would have to adapt to environmental conditions where covalent bonds are easily broken. (2.2)<br>• Ask students to describe the properties of a medical device that can buffer blood without using any chemical buffers. (2.4)<br>• Ask students to devise the potential agricultural uses of an instrument that measures the types of elements found within an intact living organism. (2.1), (2.2) |
| **Evaluation** | • Ask students to discuss the probability of life on a planet that is not abundant in the elements that form covalent bonds. (2.2)<br>• Ask students to explain which characteristics of life mentioned in Chapter 1 are determined by the properties of elements making up organisms. (2.1), (2.2), (2.3), (2.4) |

 

**VISUAL RESOURCES**

1. Molecular models are quite helpful when reinforcing the concept of molecular structure. Many aspects of chemistry such as the differences between isomers just don't work on a two-dimensional surface. Use student participation and an inexpensive object such as a tennis ball to illustrate the difference between ionic and covalent bonds. When the object is given to one student by another the recipient can walk away, no strings attached. This is similar to the exchange of electrons that form the ionic bond. When the object is held by both students, or shared as analogous to the covalent bond, the two students must remain in fairly close proximity for such sharing to be practical. (2.2)

2. In a small class setting, bring in samples of polar and nonpolar substances and mix them together. In a large class, use an overhead or videocam with LCD setup to project it to the entire class; this may take a little ingenuity when working on a horizontal surface. So, it may be useful to conduct the demonstration in plastic Petri plates. Cohesion and adhesion can also be demonstrated in this manner using coloured solutions and capillary tubes touched to the solutions. Diatec makes 35 mm deep well projection slides that are waterproof (available through Carolina or Wards Biological Companies).(2.4)

3. Energy levels are similar to a person on a pogo stick; they are either up or down, but not in between. Electrons can only change their energy in specific increments, by being up or down. This concept can be approximated by doing a bouncing action a few times with your feet. The action represents an electron in one energy state. Then represent an electron leaving and returning to its energy level by jumping high, straight up, and landing on the same spot with a thud.(2.2)

4. The characteristics of water are intuitive when related to everyday events, tempering effects on weather, sweating, surface tension, and so forth. Use as many common examples as possible. Your students can measure the relative pH of various household solutions using tea—the normal unadulterated drinking variety. Tea becomes more yellow in colour when lemon juice is added because the juice is acidic, and not because the tea is diluted by a yellow liquid. Red cabbage is also an acid-base indicator, red when acid, blue when basic. (2.4)

5. The following analogy has been quite helpful in differentiating ionic and covalent bonds: Mary is a well-prepared student who sits attentively in the front row during lecture. Normally she brings two cans of pop to lecture, orange and cola. Ann, a thirsty classmate, begs the cola from generous Mary and sits in the back row. The bond between the two students is analogous to an ionic bond. The can of pop is donated from one student to another. The bond strength between Mary and Ann is not very strong as they can sit on opposite sides of the lecture hall and still each drink a pop. David also comes to class with two cans of pop, root beer and lemon-lime. He, though, is less generous and less decisive than Mary and wants to drink both flavours of pop during lecture. When his thirsty friend Ed arrives, David decides to share his pop rather than overtly giving one can away. Ed must, therefore, sit in the seat right next to David. This is analogous to a covalent bond. David and Ed must remain in close proximity to one another and the bond

between them is quite strong, especially in comparison to the ionic bond between Mary and Ann.(2.2, 2.3)

**DEMONSTRATIONS TO SUPPORT CONCEPTS**

*These exercises can be simulcast to the lecture hall from a remote laboratory location. It requires two-way communication between the instructor in the lecture hall and the technical staff in the laboratory. All of your campus' safety protocols must be followed.*

A. Exposing the Carbon Skeleton of Organisms (2.2)

Introduction

It is difficult for students to conceptualize the presence and significance of carbon that makes up the skeleton of all organic molecules. This demonstration shows the prevalence of carbon in carbohydrates and amount of bond energy stored in organic molecules. It uses sulfuric acid to break down the covalent bonds of sucrose releasing the oxygen and hydrogen. What remains in the container is a carbon mass puffed with gases (carbon dioxide and sulfur oxides) released by the molecular degradation.

Special Precautions

Caution must be used with this demonstration. It produces a rapid burst of heat and noxious fumes. It should be done using personal protection equipment (gloves, goggles, and a laboratory apron) and in a well-vented area near a source of running water. Be careful to conduct the demonstration in a manner that cannot harm students if the glass container cracks. The waste remaining from the demonstration should be disposed of in an acid waste container.

This procedure can be shown to a large class using a videocam attached to an LCD projector.

Materials

- Large glass thermometer
- 400 ml Pyrex® or equivalent glass beaker
- Large glass test tube
- 100 ml of water
- Bottle of sucrose solution with dropper (20g sucrose/100 ml water)
- Bottle of concentrated sulfuric acid solution with dropper
- Roll of aluminum foil
- Personal protection equipment

Procedure

1. Explain to the class that you will be demonstrating the elemental composition of sucrose.
2. Lay down a sheet of aluminum foil on the table where the demonstration will take place.
3. Place the beaker in the middle of the foil.

 

4. Add 100 ml of water to the beaker.
5. Place the test tube into the beaker.
6. Add 5 ml of sucrose solution to the test tube while explaining your action to the class.
7. Place the thermometer in the beaker so that the bulb is touching the base of the test tube.
8. Announce to the class the starting temperature of the solution.
9. Slowly add approximately 2 ml of the concentrated sulfur acid. (Do not mix or stir.)
10. Direct the class to observe what happens. (The solution will darken followed by the rapid eruption of a black column of "puffy material."
11. Announce to the class the final temperature of the solution.

Inquiry Questions

1. Ask the class to explain the elemental composition of the "puffy material." (They should be directed to answer, carbon with hydrogen gas and carbon dioxide.)
2. Ask the class to explain the temperature elevation. (They should explain it was due to the energy released by the breakage of covalent bonds.)
3. Ask the students what they should expect to find if a similar demonstration was performed on the following materials:
    - Piece of meat
    - Lump of bacon fat
    - A solution of salt
    - A piece of paper

B. Principles of Molecular Toxicology (2.2)

Introduction

The function of biological molecules is highly dependent on environmental factors such as pH, salinity, and temperature. This demonstration clearly shows the fragility of biological molecules when placed in environments that are not conducive to most living organisms. It uses egg albumin as a model for investigating environmental conditions that denature biological molecules.

Materials

- Overhead projector or videocam attached to LCD
- Petri plate or clear flat dish
- Egg albumin solution or the liquid egg white from one large egg
- Bottle of 5M hydrochloric acid with dropper
- Bottle of 5M sodium hydroxide with dropper
- Bottle of 26g/100ml water solution of copper sulfate with dropper
- Bottle of 10g/100ml sodium hydroxide solution with dropper
- Bottle of 70% ethanol with dropper

Procedure & Inquiry Questions

1. Introduce the concept of denaturation to the class.
2. Place the Petri plate on the overhead or focus on it with the videocam.
3. Add egg white to the Petri plate until it forms a 1/2cm uniform coating on the surface of the plate while explaining to the class what you are doing.
4. Ask students to describe the observable characteristics of the egg white.
5. Add 2 drops of 5M hydrochloric acid and ask the class to observe what they have seen (the egg white curdles as if it were cooked—denaturation of the proteins).
6. Ask the students what properties of the hydrochloric acid caused the proteins to denature.
7. Add 2 drops of 5M sodium hydgroxide and ask the class to observe what they have seen (the egg white curdles as if it were cooked - denaturation of the proteins).
8. Ask the students what properties of the sodium hydroxide caused the proteins to denature.
9. Add 2 drops of copper sulfate and ask the class to observe what they have seen (the egg white curdles as if it were cooked—denaturation of the proteins).
10. Ask the students what properties of the copper sulfate caused the proteins to denature.
11. Add 2 drops of sodium hydroxide and ask the class to observe what they have seen (the egg white curdles as if it were cooked—denaturation of the proteins).
12. Ask the students what properties of the sodium hydroxide caused the proteins to denature.
13. Follow up by summarizing the conformational changes that likely took place to the tertiary structure of the albumin.

## LABORATORY IDEAS

Laboratory activities are excellent ways of reinforcing complex biological principles. The following inquiries can be used as the basis of student-designed laboratory activities.

A. Water Chemistry: Water Hardness (2.4)
   a. Have students measure the hardness of different water samples as an indicator of water quality. (Water hardness is a measure of calcium or magnesium ions.)
   b. The students should be asked to design an experiment that compares water hardness to any measurable properties of water and the usability of water to humans.
   c. Students should also be directed to look up the chemistry and causes of water hardness.

 

d. Provide students with the following materials to carry out the experiment:
    i. Rain water and tap water from students' homes and from around the school.
    ii. Hard water standard composed of 203 g of Magnesium chloride crystals and 147.0 g calcium chloride crystals dissolved in 1 liter of distilled water
    iii. Distilled water negative control
    iv. Hard water test kit
    v. Thermometers
    vi. Timers
    vii. Electric heater with beaker to making boiling water bath
    viii. Access to a freezer
    ix. Universal pH paper
    x. Liquid dish soap
    xi. Suction cups and a glass surface
    xii. Grease pencil or permanent marker
    xiii. Large test tubes
    xiv. Test tube racks
    xv. Goggles

B. pH of life: (2.4)
  a. Have students test the pH of various living substances.
  b. They should be asked to predict the expected pH values for various living materials.
  c. The students should be directed to make hypotheses about any variations in pH from their expected predictions. They should also be asked to investigate the reason why certain parts of organisms may vary greatly from a neutral pH.
  d. Provide students with the following materials to carry out the experiment:
    i. Universal pH paper
    ii. Instruments for cutting the animal and plant samples
    iii. Fresh mushrooms
    iv. Fresh lemons or grapefruits
    v. Potatoes
    vi. Tomatoes
    vii. Apples
    viii. Broccoli
    ix. Beef or chicken livers
    x. Imitation crab meat chunks (tuna and other fish muscle wastes)
    xi. Goggles

C. Use of pH and salts in food preservation using the catalase test. (2.4)
   a. Explain to students that a chemical produced in health cells called catalase is an indicator of cell metabolism. Then explain that certain metabolic pathways associated with catalase cause the decay of certain foods such as vegetables.
   b. Demonstrate the catalase test by adding hydrogen peroxide to a fresh section of potato (the test material). Bubbling (or the production of oxygen gas) is an indicator of catalase activity.
   c. Ask the students to design a controlled experiment that investigates the ability pH and certain salt concentrations to preserve food.
   d. Students should also be asked what would be the most feasible pH or salt levels that preserve food while also maintaining edibility.
   e. Provide students with the following materials:
      i. Potatoes
      ii. Instruments for cutting the potato samples
      iii. Petri plate halves or a surface for testing the potatoes for catalase
      iv. Household hydrogen peroxide
      v. Droppers
      vi. pH solutions (tablets are available that when added to water provide a buffered solution at a particular pH)
         1. pH 2
         2. pH 4
         3. pH 6
         4. pH 7
         5. pH 8
         6. pH 10
         7. pH 12
      vii. Salt solutions (sodium chloride)
         1. 0% (distilled water)
         2. 0.5 %
         3. 1%
         4. 3 % (close to sea water)
         5. 5%
         6. 10%
   f. The students should first add a drop of the test solutions and let it soak into a small slice of potato. They should then add the catalase to see if catalase activity was hindered or enhanced.

 

## LEARNING THROUGH SERVICE

Service learning is a strategy of teaching, learning and reflective assessment that merges the academic curriculum with meaningful community service. As a teaching methodology, it falls under the category of experiential education. It is a way for students to carry out volunteer projects in the community for public agencies, nonprofit agencies, civic groups, charitable organizations, and governmental organizations. It encourages critical thinking and reinforces many of the concepts learned in a course.

Students who have successfully mastered the content of Chapter 2 can apply their knowledge for service learning activities in the following ways:

1. Have students judge science fairs that focus on projects that investigate the chemistry of biological molecules.
2. Have students tutor middle school or high school biology students studying the molecules of life.

## ETYMOLOGY OF KEY TERMS

| | |
|---|---|
| amphi- | two; both (from the Greek *amphi*- on both sides) |
| ana- | up; back (from the Greek *an*- up) |
| cat- | down (from the Greek *kata*- down) |
| colligative | depending upon the number of molecules not the specific type (from the Latin *colligatus*- tying together) |
| hydro- | of, or pertaining to, water (from the Greek *hydor*- water) |
| ion- | an electrically charged atom or group of atoms (from the Greek *ion*going) |
| electro- | pertaining to or involving electricity (from the Greek *electron*amber) |
| equi- | equal (from the *Latin aequus*- equal) |
| -gen | that which produces (from the Greek *genes*- born or produced) |
| libri | balance (from the Latin *libra*- balance) |
| lys (lysis) | dissolution; breaking (from the Greek *lysis*- dissolution) |
| neutro- | neutral; having no charge or affiliation (from the Latin *neuter*neither) |
| -pathic | feeling; suffering (from the Greek *pathos*- suffering or feeling) |

 

| | |
|---|---|
| proto- | first (from the Greek *protos*- first) |
| radio- | dealing with radiant energy; emitting rays (from the Latin *radius*ray) |
| solute | substance dissolved in a solution (from the Latin *solutus*, past participle of *solvere*- to loosen) |
| solvent | a substance that dissolves another to form a solution (from the Latin *solvent*, the stem of *solvens*, which is the present participle of *solvere*- to loosen) |

 