# Notes to Instructors

## Chapter 2 The Chemical Context of Life
## Chapter 3 Water and the Fitness of the Environment

## What is the focus of these activities?

Living organisms function in the real world, so they are subject to all the laws of chemistry and physics. In addition, biological organisms and systems are variable. No two organisms are exactly alike, and no two systems are identical in form or function. As a result, our analysis of such systems tends to deal with statistical averages or probabilities. This means that it is difficult to understand biological systems without having a good basic understanding of chemistry, physics, and math (including probability and statistics).

The vast majority of introductory biology students have studied inorganic chemistry in their high school and first-year college chemistry courses. Many students compartmentalize their knowledge, however. In some cases, the compartmentalization is so extreme that the students feel uncomfortable dealing with chemical formulas and ideas outside of chemistry classes. Therefore, it is generally useful to review some of the basic ideas in chemistry and, at the same time, demonstrate how they can be applied to understanding biological systems.

## What are the particular activities designed to do?

### Activity 2.1 A Quick Review of Elements and Compounds

The questions in this activity are designed to help students review and understand:

- atomic/molecular number, mass number, and atomic/molecular weight and how they can be used to determine the reactivity of elements;
- various types of chemical bonds and how they affect the structure and energetics of molecules; and
- the difference between a mole and a molar equivalent and how knowledge of these can be used in biological applications.

### Activity 3.1 A Quick Review of the Properties of Water

The questions in this activity are designed to help students review and understand the properties of water and how they support life. Students are asked to review these key properties:

- $H_2O$ molecules are cohesive; they form hydrogen bonds with each other.
- $H_2O$ molecules are adhesive; they form hydrogen bonds with polar surfaces.
- Water is a liquid at normal physiological (or body) temperatures.
- Water has a high specific heat.
- Water has a high heat of vaporization.
- Water's greatest density occurs at 4°C.

In addition, students review pH and how it is related to both the ionization constant of pure water and the concentration of $H^+$ ions in a solution.

## What misconceptions or difficulties can these activities reveal?

### Activity 2.1

Question 1: Many students don't understand that nutrients for plants are inorganic and most nutrients for animals (heterotrophs) are organic.

Questions 2 and 3: Most students know how to balance a chemical equation. Fewer understand the relationship between molecules of a substance and moles of that substance. Similarly, most students can recite what a mole is; however, the majority have not thought about how that knowledge can be applied. Therefore, much of this first activity is devoted to making it clear that a balanced equation indicates not only the number of molecules required but also the number of moles required. It also explains why moles can be substituted for molecules in such equations.

Question 4: Some students have difficulty understanding that a solution's concentration or molarity does not change if you aliquot, or subdivide, the solution into smaller volumes. To test this, ask your students: "There is 10% sugar in this solution. If I pour half of it into one beaker and the other half into another beaker, what percent sugar will I have in each beaker?" More than half of the students will automatically answer 5%.

Questions 5 and 6: These questions are designed to help students understand how a knowledge of balanced equations and molar equivalents can be useful in biology.

Questions 7 and 8: The answers go into a little more detail than does *Campbell Biology*, 11th edition. Students obviously shouldn't be asked to know the specific electronegativity of each of the elements. However, using concrete numbers may help students understand how their electronegativity is related to the type of bonds formed between elements.

### Activity 3.1

Most students have no difficulty stating the properties of water and the definition of pH. On the other hand, not all of them have a good understanding of how these properties are related to biological and other phenomena. Therefore, some questions ask students to relate pH values to actual concentrations of $H^+$ ions in solution and to relate the properties of water to common experiences they have had in class or in life.

# Answers

## Activity 2.1 A Quick Review of Elements and Compounds

1. Table 2.1 (page 29) lists the chemical elements that occur naturally in the human body. Similar percentages of these elements are found in most living organisms.

| a. In what abiotic (nonlife) chemical forms are these elements often found in nature? | b. In what chemical form(s) do animals need to obtain these elements? | c. In what chemical form(s) do plants need to obtain these elements? |
|---|---|---|
| These elements are most commonly found as $CO_2$, $N_2$, and $O_2$ in the atmosphere and as $H_2O$, $PO_4$, and S compounds on Earth. | With the exception of oxygen and water, animals obtain the majority of these elements in the form of organic compounds. | Plants can obtain C as $CO_2$, N as ammonia or nitrite or nitrates, phosphorus as phosphates, sulfur as sulfides or sulfates, and so on. In other words, plants obtain these elements as inorganic compounds. |

2. A chemical element cannot be broken down to other forms by chemical reactions. Each element has a specific number of protons, neutrons, and electrons.

   a. What is the name of the following element, and how many protons, neutrons, and electrons does it have?

11
Na
23

| Name | Number of protons | Number of neutrons | Number of electrons |
|---|---|---|---|
| Sodium | 11 | 12 | 11 |

b. What information do you need to calculate or determine the following?

| The atomic number of an element | The mass number of an element | The weight in daltons of one atom of an element |
|---|---|---|
| The atomic number is equal to the number of protons (or electrons). | The mass number is equal to the number of protons plus the number of neutrons. | You can estimate the weight in daltons as 1 dalton per proton or neutron. Therefore, the weight in daltons of an element is approximately equal to the number of protons plus the number of neutrons. |

c. What are the atomic number, mass number, and weight in daltons of the element shown in part a?

| Atomic number | Mass number | Weight in daltons |
|---|---|---|
| 11 | 23 | 23 |

3. One mole of an element or compound contains $6.02 \times 10^{23}$ atoms or molecules of the element or compound. One mole of an element or compound has a mass equal to its mass number (or molecular weight) in grams. For example, 1 mole of hydrogen gas ($H_2$) contains $6.02 \times 10^{23}$ molecules and weighs 2 g.

| a. What is the weight of 1 mole of pure sodium (Na)? | b. How many molecules of Na are in 1 mole of Na? |
|---|---|
| 23 g | $6.02 \times 10^{23}$ |

c. How would you determine how many grams are in a mole of any chemical element or compound?

A mole of any chemical element or compound is equal to the mass number in grams of that mole or compound. For example, the mass number of Na is 23; therefore, a mole of Na has a mass of 23 g. The mass number of water is 18; therefore, a mole of water has a mass of 18 g.

4. One atom of Na can combine with one atom of Cl (chlorine) to produce one molecule of NaCl (table salt).

| a. If Cl has 17 electrons, 17 protons, and 18 neutrons, what is its mass number? | b. What is the mass number of NaCl? | c. How many grams of NaCl equal a mole of NaCl? |
|---|---|---|
| 35 | $23 + 35 = 58$ | 58 g |

d. If you wanted to combine equal numbers of Na and Cl atoms in a flask, how much Cl would you have to add if you added 23 g of Na? (Include an explanation of the reasoning behind your answer.)

23 g of Na is equal to 1 mole of Na. A mole contains $6.02 \times 10^{23}$ molecules of the substance. To add an equal number of molecules of Cl, you need to add 1 mole of Cl, or 35 g.

e. To make a one-molar (1 *M*) solution of NaCl, you need to add 1 mole of NaCl to distilled water to make a final volume of 1 L (1,000 mL). A 1 *M* solution is said to have a molarity of 1. If you added 2 moles of NaCl to 1 L of distilled water, you would make a 2 *M* solution and its molarity would equal 2. You make up a 1 *M* solution of NaCl.

| How many molecules of NaCl are in the 1 *M* NaCl solution? | How many molecules of NaCl are there per mL of the solution? |
|---|---|
| If you used 1 L of water to make the 1 *M* solution, you would have $6.02 \times 10^{23}$ molecules in the liter. | To calculate the number of molecules per mL, divide $6.02 \times 10^{23}$ by $1{,}000 = 6.02 \times 10^{20}$ molecules/mL. |

f. Next, you divide this 1 *M* solution of NaCl into four separate flasks, putting 250 mL into each flask.

| How many grams of NaCl are in each flask? | How many molecules of NaCl are in each flask? | How many molecules of NaCl are there per mL of distilled water? | What is the molarity of NaCl in each of the four flasks? |
|---|---|---|---|
| $58/4 = 14.5$ g | $6.02 \times 10^{23}$ divided by $4 = 1.51 \times 10^{23}$ | $6.02 \times 10^{20}$ | 1 *M* |

5. The summary formula for photosynthesis is

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

| a. How many molecules of carbon dioxide and water would a plant have to use to produce three molecules of glucose ($C_6H_{12}O_6$)? | b. How many moles of carbon dioxide and water would a plant have to use to produce 2 moles of glucose? |
|---|---|
| For each molecule of glucose produced, 6 molecules of carbon dioxide and 6 molecules of water are consumed. Therefore, the plant would need to use 18 molecules of each. | Because a mole of anything contains the same number of molecules, the plant would need to use 6 times as many moles of carbon dioxide and water, or 12 moles of each. |

c. Refer to the summary formula for photosynthesis. If you know the number of molecules or moles of any of the reactants used (or products produced), how would you calculate the number of molecules or moles of all of the other reactants needed and products produced?

If the formula is balanced and if it is a true representation of the overall reactions that occur, then the numbers in front of each reactant and product indicate the molecular or molar equivalents required for the reactions.

*Note:* To represent the actual reactants required and products produced, the overall formula for photosynthesis is more correctly stated as:

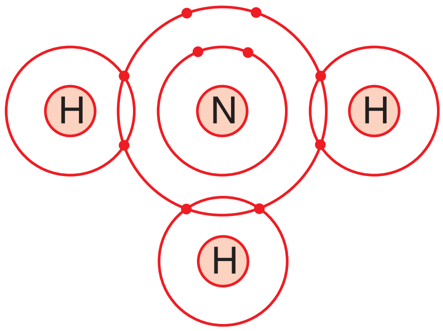
$6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$

In most texts, however, this is reduced to $6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$

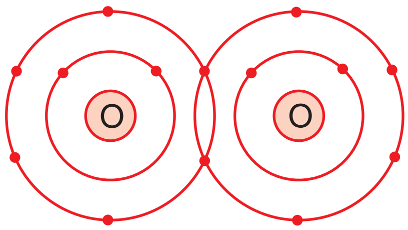
6. A biologist places a plant in a closed chamber. A sensor in the chamber maintains the carbon dioxide level at the normal atmospheric concentration of 0.03%. Another sensor allows the biologist to measure the amount of oxygen produced by the plant over time. If the plant produces 0.001 mole of oxygen in an hour, how much carbon dioxide had to be added to the chamber during that hour to maintain the atmospheric concentration of 0.03%?

   For every mole of oxygen produced, 1 mole of carbon dioxide had to be consumed. Therefore, 0.001 mole of carbon dioxide had to be added to maintain a constant level of $CO_2$ in the chamber.

7. $O_2$ and $NH_3$ are both small covalent molecules found in cells. $NH_3$ is extremely soluble in the aqueous environment of the cell, while $O_2$ is relatively insoluble. What is the basis for this difference in solubility between the two molecules? In reaching your answer, draw the structures of the molecules as valence shell diagrams (as in Figure 2.12). Given these diagrams, consider the types of interactions each molecule could have with water.



Ammonia ($NH_3$)

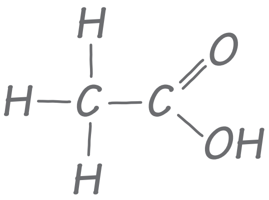


Oxygen ($O_2$)

Ammonia is a polar molecule much like water. The N in it is relatively negative, and the Hs are relatively positive. Polar substances tend to be more soluble in water. $O_2$, on the other hand, is not polar.

8. Refer to Chapter 2 of *Campbell Biology*, 11th edition, which describe these types of chemical bonds: nonpolar and polar covalent bonds, ionic bonds, hydrogen bonds, and van der Waals interactions.

The molecule diagrammed here can also be represented by the formula $CH_3COOH$.



Explain how you could determine which of the bonds between elements in this molecule are polar or nonpolar covalent bonds, ionic bonds, hydrogen bonds, and van der Waals interactions.

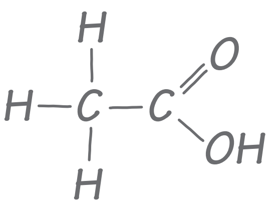
The best way to determine the bond types is to determine each atom's electronegativity, or its attraction for electrons. As a general rule, the more filled the outer electron shell of an atom is, the higher is its electronegativity. In addition, the fewer electron shells, the greater the electron negativity. As a result, an atom's attraction for electrons increases as you go from left to right in the periodic table. Electronegativity values tend to decrease as you go from top to bottom of the periodic table. To determine whether bonds are ionic, polar covalent, or nonpolar covalent, you need to determine the difference in electronegativity between the atoms that make up a molecule. If the difference in electronegativity is small, the bond is likely to be nonpolar covalent. If the difference is very large, the bond is likely to be ionic. Intermediate differences produce polar covalent bonds. The following table lists specific electronegativity values for selected elements.

| | | | | | | |
|---|---|---|---|---|---|---|
| H = 2.1 | | | | | | |
| Li = 1.0 | Be = 1.5 | B = 2.0 | C = 2.5 | N = 3.0 | O = 3.5 | F = 4.0 |
| Na = 0.9 | Mg = 1.2 | Al = 1.5 | Si = 1.8 | P = 2.1 | S = 2.5 | Cl = 3.0 |

Using specific electronegativity values, you can determine the type of bond: If the difference in electronegativity between two atoms in a compound is less than 0.5, the bond is nonpolar covalent. If the difference is between 0.5 and 1.6, the bond is polar covalent. If the difference is greater than 1.6, the bond is ionic.

# Activity 3.1 A Quick Review of the Properties of Water

1. Compounds that have the capacity to form hydrogen bonds with water are said to be hydrophilic (water loving). Those without this capacity are hydrophobic (water fearing).

| | |
|---|---|
|  | Is the molecule on the left hydrophilic or hydrophobic? Explain your answer.<br>This molecule is acetic acid. The $-$COOH group is polar, which makes this molecule hydrophilic. |

2. In addition to being polar, water molecules can dissociate into hydronium ions ($H_3O^+$, often described simply as $H^+$) and hydroxide ions ($OH^-$). The concentration of each of these ions in pure water is $10^{-7}$. Another way to say this is that the concentration of hydronium ions, or $H^+$ ions, is one out of every 10 million molecules. Similarly, the concentration of $OH^-$ ions is one in 10 million molecules.

   a. The $H^+$ ion concentration of a solution can be represented as its pH value. The pH of a solution is defined as the negative $\log_{10}$ of the hydrogen ion concentration. What is the pH of pure water?

   The hydrogen ion concentration of pure water is $10^{-7}$. The $\log_{10}$ of $10^{-7}$ is $-7$. The negative $\log_{10}$ of $10^{-7}$ is therefore +7.

   b. Refer to the diagram of the molecule of acetic acid in question 1. The COOH group can ionize to release a $H^+$ ion into solution. If you add acetic acid to water and raise the concentration of $H^+$ ions to $10^{-4}$, what is the pH of this solution?

   The pH of a solution with a $H^+$ ion concentration of $10^{-4}$ is 4.

3. Life as we know it could not exist without water. All the chemical reactions of life occur in aqueous solution. Water molecules are polar and are capable of forming hydrogen bonds with other polar or charged molecules. As a result, water has the following properties:
   A. $H_2O$ molecules are cohesive; they form hydrogen bonds with each other.
   B. $H_2O$ molecules are adhesive; they form hydrogen bonds with polar surfaces.
   C. Water is a liquid at normal physiological (or body) temperatures.
   D. Water has a high specific heat.
   E. Water has a high heat of vaporization.
   F. Water's greatest density occurs at 4°C.

Explain how these properties of water are related to the phenomena described in parts a–h below. More than one property may be used to explain a given phenomenon.

a. During the winter, air temperatures in the northern United States can remain below 0°C for months; however, the fish and other animals living in the lakes survive.

Water's greatest density occurs at 4°C. In a lake, the 4°C water sinks below the water that is colder (or warmer). As a result, 0°C water is less dense than 4°C water. In addition, as it freezes, water takes on a crystalline structure and becomes ice. Ice has a density of about 0.92 g/cm$^3$, pure water at 0°C has a density of about 0.99 g/cm$^3$, and pure water at 4°C has a density of 1.0 g/cm$^3$. The ice on top of a lake acts like insulation and, as a result, most deep lakes do not freeze to the bottom.

b. Many substances—for example, salt (NaCl) and sucrose—dissolve quickly in water.

Water is very polar. The attraction of the polar water molecules for the $Na^+$ and $Cl^-$ ions of NaCl is strong enough to allow them to dissociate and interact with water molecules (dissolve).

c. When you pour water into a 25-mL graduated cylinder, a meniscus forms at the top of the water column.

Water is attracted to the polar molecules that make up the glass (or plastic) cylinder. At the same time, they are attracted to each other. As a result, some of the water molecules associate with the polar molecules of the cylinder and are apparently "pulled up" the inside edge of the cylinder.

d. Sweating and the evaporation of sweat from the body surface help reduce a human's body temperature.

Water has a high specific heat. The specific heat of water is 1 cal/g/°C. In other words, it takes 1 calorie of heat to change the temperature of 1 g of water 1°C. In addition, water has a high latent heat of vaporization (540 cal/g at 100°C). This can be thought of as the additional heat required to break apart polar water molecules so that they can move from the liquid to the gaseous state. As a result, evaporation (change of water from liquid to gaseous state) carries with it large amounts of heat.

e. A bottle contains a liquid mixture of equal parts water and mineral oil. You shake the bottle vigorously and then set it on the table. Although the law of entropy favors maximum randomness, this mixture separates into layers of oil over water.

The oil molecules are nonpolar and hydrophobic. The water molecules are polar and cohesive. As a result, the water molecules tend to interact strongly with each other and exclude the oil molecules. The oil layers on top of the water because it is less dense than water.

f. Water drops that fall on a surface tend to form rounded drops or beads.

Water molecules are cohesive and form hydrogen bonds with each other. As a result, a drop of water tends to bead up or become rounded.

g. Water drops that fall on your car tend to bead or round up more after you polish (or wax) the car than before you polished it.

The wax (or polish) is hydrophobic and therefore less polar than the surface was likely to be before you polished it. Because the adhesion between the surface and the water molecules is lower, the cohesion of the water molecules for each other appears even more dramatic.

h. If you touch the edge of a paper towel to a drop of colored water, the water will move up into (or be absorbed by) the towel.

The polar water molecules adhere to the cellulose in the paper towel and cohere to each other. As a result, they are drawn up into the towel. The same mechanism accounts for the movement of water molecules up capillary tubes.

# Notes to Instructors

## Chapter 4 Carbon and the Molecular Diversity of Life
## Chapter 5 The Structure and Function of Macromolecules

## What is the focus of these activities?

The activities associated with Chapters 2 and 3 provided students with a review of some of the basics of inorganic chemistry. The activities associated with Chapters 4 and 5 deal with organic chemistry and biochemistry. Although most introductory biology students have had some exposure to inorganic chemistry, fewer have had courses in organic chemistry or biochemistry. Therefore, these activities are designed with these goals in mind:

- Help students identify the major differences among the four main types of biological macromolecules: carbohydrates, lipids, proteins, and nucleic acids.
- Recognize what functional groups are and how they can modify the general properties and functions of organic compounds.
- Use their understanding from the goals above to predict how various structural modifications can affect the behavior of macromolecules.

## What are the particular activities designed to do?

### Activity 4.1/5.1 How can you identify organic macromolecules?

This activity is designed to help students easily recognize carbohydrates, lipids, proteins, and nucleic acids when viewed as chemical structures. Students develop some simple rules to make it easier for them to recognize differences among the general chemical structures of carbohydrates, lipids, proteins, and nucleic acids. This type of activity is especially important for the many introductory biology students who have not yet had organic chemistry or biochemistry.

### Activity 4.2/5.2 What predictions can you make about the behavior of organic macromolecules if you know their structure?

In this activity, students examine the general properties of organic macromolecules. In particular, they examine the properties of functional groups and how these can modify the behavior of macromolecules. This includes how modifying functional groups can affect the water solubility and the chemical reactivity of molecules.

At the end of this activity, students are asked to predict how various macromolecules could react if placed in specific environments or if modified in specific ways. Answering these questions requires students to integrate and use understanding they have gained from Chapters 2–5.

## What misconceptions or difficulties can these activities reveal?

**Activity 4.1/5.1**

Question 1, Part A: This question asks for the C:H:O ratio of the various macromolecules. For carbohydrates, it is approximately 1:2:1. For many lipids, it is approximately 1:2:very few. And for proteins and nucleic acids, there is no reliable ratio of C:H:O. Many students become upset that the answer for proteins and nucleic acids is "no reliable ratio of C:H:O." Remind them that they would not have known the C:H:O ratio was not a good predictor for these molecules unless they investigated it. Answers like this just mean we need to look for other ways of identifying these molecules. Some of these other ways include looking for specific functional groups, for example amino and carboxyl groups in amino acids and ribose versus deoxyribose and specific nucleotides to identify RNA versus DNA.

Part B: After developing their own rules for identifying macromolecules, most students won't have difficulty identifying these structures as carbohydrate, protein, lipid, or nucleic acid. It is best to present this activity in that light; that is, let students know that the purpose of the activity is to help them prove it is possible to categorize complex macromolecules using only a few simple rules.

**Activity 4.2/5.2**

Question 1: The table asks students to look at different possible characteristics of R groups.

| R group | Basic, acidic, or neutral | Polar or nonpolar | Hydrophilic or hydrophobic |
|---|---|---|---|

This question helps students understand, for example, that something that is polar is also hydrophilic; that is, these designations are not mutually exclusive. In addition, by learning the characteristics of key functional groups, students will have a better understanding of how modifications in macromolecular structure can lead to modifications in function.

Question 4: The first three experiments ask students to examine how phospholipids (and glucose) will distribute themselves in different kinds of aqueous environments. Many students have memorized that phospholipids can form bilayers or micelles in aqueous environments, and they have the misconception that phospholipids will organize into micelles or bilayers under any circumstance.

# Answers

## Activity 4.1/5.1 How can you identify organic macromolecules?

Refer to the figure (Some Simple Chemistry) on the next page when doing this activity.

**Part A. Answer the questions. Then use your answers to develop simple rules for identifying carbohydrates, lipids, proteins, and nucleic acids.**

1. What is the approximate C:H:O ratio in each of the following types of macromolecules?

| Carbohydrates | Lipids | Proteins | Nucleic acids |
|---|---|---|---|
| 1:2:1 | 1:2:very few | There is no reliable C:H:O ratio for proteins. | There is no reliable C:H:O ratio for nucleic acids. |

2. Which of the compounds listed in question 1 can often be composed of C, H, and O alone?

   Carbohydrates and lipids can often be composed of C, H, and O alone.

3. Which of the compounds can be identified by looking at the C:H:O ratios alone?

   Only carbohydrates and some lipids can be identified using C:H:O ratios alone.

4. What other elements are commonly associated with each of these four types of macromolecules?

|  | Carbohydrates | Lipids | Proteins | Nucleic acids |
|---|---|---|---|---|
| Always contain P | No | No (except for phospholipids) | No | Yes |
| Generally contain no P* | Yes | Yes (except for phospholipids) | Yes | No |
| Always contain N | No | No | Yes | Yes |
| Generally contain no N | Yes | Yes | No | No |
| Frequently contain S | No | No | Yes | No |
| Generally contain no S | Yes | Yes | No | Yes |

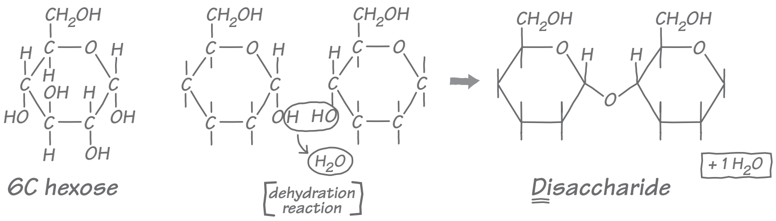
[*] *Note:* It is possible to find some exceptions in each of these categories where "Yes" is the answer to "Generally contain no ___." For example, in reaction sequences many compounds undergo phosphorylation. However, if the natural state of the compound does not contain P (for example) the answer to "Generally contain no P" would be yes.

# Some Simple Chemistry

**Compound** — Basic components ➡ Reaction ➡ Product

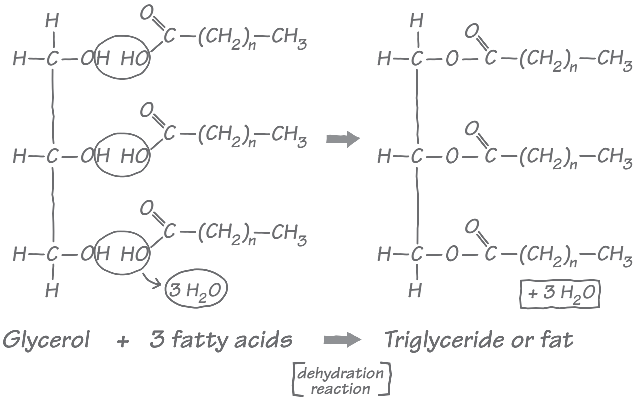
## Carbohydrates:

Sugars, starches, glycogen, cellulose



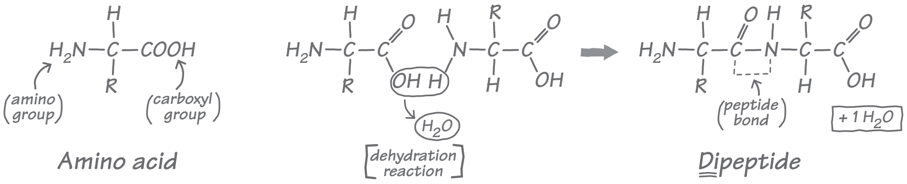
## Lipids:

Fats, oils, waxes, cholesterol



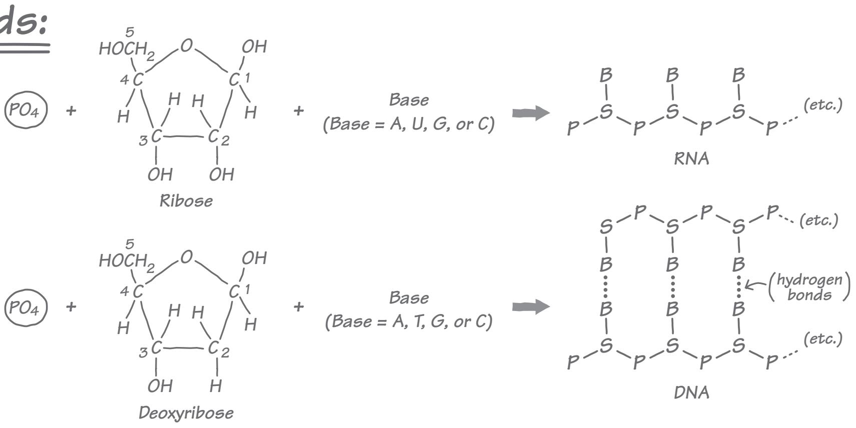
## Proteins:

Enzymes, structural proteins



## Nucleic acids:

DNA, RNA



5. Functional groups can modify the properties of organic molecules. In the following table, indicate whether each functional group is polar or nonpolar and hydrophobic or hydrophilic. Which of these functional groups are found in proteins and lipids?

| Functional group | Polar or nonpolar | Hydrophobic or hydrophilic | Found in all proteins | Found in many proteins | Found in many lipids |
|---|---|---|---|---|---|
| —OH | Polar | Hydrophilic | No | In some R groups | In fatty acids as terminal reactive group |
| —$CH_2$ | Nonpolar | Hydrophobic | No | Yes in side groups | Yes |
| —COOH | Polar | Hydrophilic | Yes | | No |
| —$NH_2$ | Polar | Hydrophilic | Yes | | No |
| —SH | Polar | Hydrophilic | No | Found in cysteine | No |
| —$PO_4$ | Polar | Hydrophilic | No | Only if they have been phosphorylated | In phospholipids |

6. You want to use a radioactive tracer that will label only the protein in an RNA virus. Assume the virus is composed of only a protein coat and an RNA core. Which of the following would you use? Be sure to explain your answer.

a. Radioactive P b. Radioactive N c. Radioactive S d. Radioactive C

To distinguish between protein and RNA in a virus, you could use radioactively labeled S compounds. If you grew viruses on cells with radioactively labeled S compounds, the sulfhydryl groups in the virus's protein would become labeled but the RNA would not become labeled.

7. Closely related macromolecules often have many characteristics in common. For example, they share many of the same chemical elements and functional groups. Therefore, to separate or distinguish closely related macromolecules, you need to determine how they differ and then target or label that difference.

a. What makes RNA different from DNA?

RNA contains ribose sugar, whereas DNA contains deoxyribose sugar. In addition, RNA contains uracil and not thymine. DNA contains thymine but not uracil.

b. If you wanted to use a radioactive or fluorescent tag to label only the RNA in a cell and not the DNA, what compound(s) could you label that is/are specific for RNA?

You could label either ribose or uracil.

c. If you wanted to label only the DNA, what compound(s) could you label?

You could label either deoxyribose or thymine.

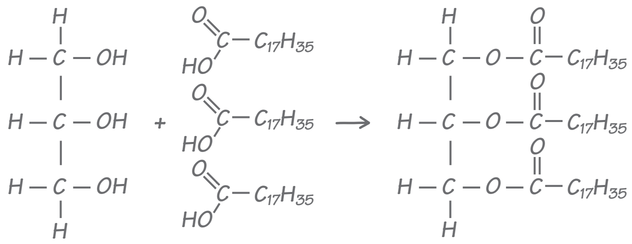
8. Based on your answers to questions 1–7, what simple rule(s) can you use to identify the following macromolecules?

| | |
|---|---|
| Carbohydrates | Look for a 1:2:1 C:H:O ratio. Many carbohydrates will contain no P, N, or S. |
| Lipids | Look for a 1:2 ratio of C:H and only very small amounts of O. Most will contain no S. Phospholipids can contain P and N (as part of the choline group; see Figure 5.11 in *Campbell Biology*, 10th edition). |
| Proteins | Look for amino and carboxyl groups. Some contain S. All proteins can be identified by the presence of peptide bonds. (See Figure 5.15 for the structure of a peptide bond.) |
| Nucleic acids | Look for nucleotides made up of a five-carbon sugar, a phosphate group, and a nitrogenous base. |
| DNA versus RNA | DNA contains phosphate, deoxyribose sugar, and adenine, guanine, cytosine, and thymine. RNA contains phosphate, ribose sugar, and adenine, guanine, cytosine, and uracil. |

## Part B. Carbohydrate, lipid, protein, or nucleic acid? Name that structure!

Based on the rules you developed in Part A, identify the compounds below (and on the following page) as carbohydrates, lipids, amino acids, polypeptides, or nucleic acids. In addition, indicate whether each is likely to be polar or nonpolar, hydrophilic or hydrophobic.

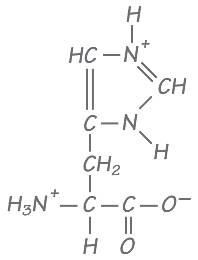
1)



1) lipid (fat or triglyceride)

Hydrophobic and nonpolar

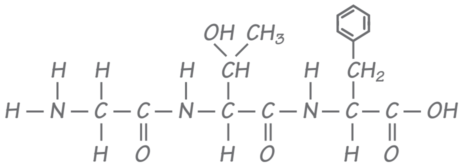
2)



2) amino acid

The amino and carboxyl group would make this somewhat polar and hydrophilic.

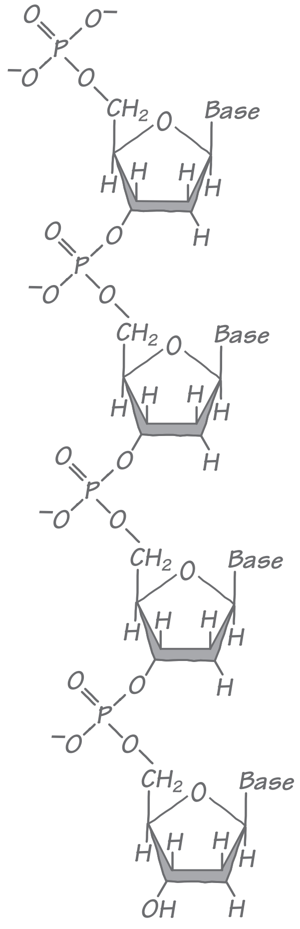
3)



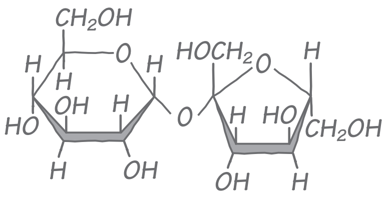
3) a tripeptide made up of 3 amino acids

The R groups are hydrophobic with the possible exception of the −OH group. The amino and carboxyl groups are hydrophilic and polar.

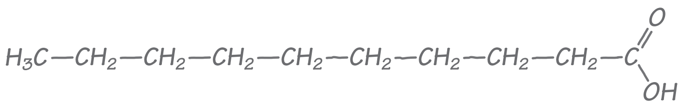
4)



5)

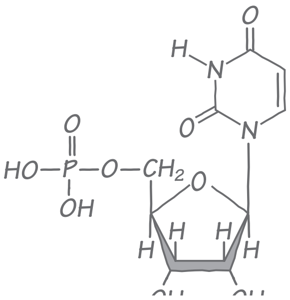


6)

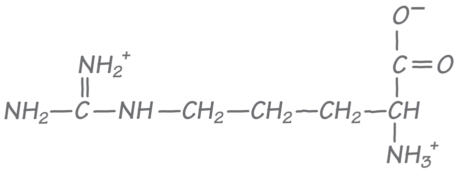


$H_3C{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}\overset{\diagup\!\!\!\diagup O}{\underset{\diagdown OH}{C}}$

7)

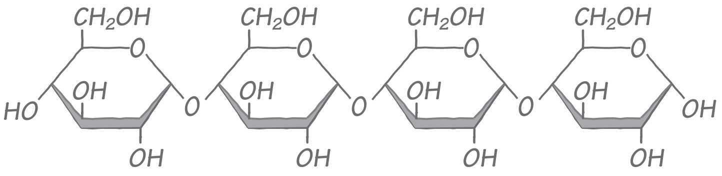


8)

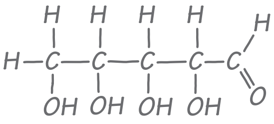


$NH_2{-}\overset{NH_2^+}{\overset{\|}{C}}{-}NH{-}CH_2{-}CH_2{-}CH_2{-}\underset{\begin{array}{c}|\\NH_3^+\end{array}}{\overset{\begin{array}{c}O^-\\|\\C{=}O\\|\end{array}}{CH}}$

9)



10)



$H{-}\overset{\overset{H}{|}}{\underset{\underset{OH}{|}}{C}}{-}\overset{\overset{H}{|}}{\underset{\underset{OH}{|}}{C}}{-}\overset{\overset{H}{|}}{\underset{\underset{OH}{|}}{C}}{-}\overset{\overset{H}{|}}{\underset{\underset{OH}{|}}{C}}{-}\overset{\diagup H}{\underset{\diagdown\!\!\!\diagdown O}{C}}$

4) single strand of 4 bases in DNA

Because of the phosphate groups DNA tends to be negatively charged and therefore somewhat polar.

5) disaccharide sugar or carbohydrate

This compound is hydrophilic and polar.

6) fatty acid

Hydrophobic and nonpolar with the exception of the carboxyl group.

7) ribonucleotide

Again the phosphate group is polar.

8) amino acid

The amine and carboxyl groups are polar.

9) polysaccharide

Polysaccharides made up of many monosaccharide subunits (like this part of a glycogen molecule) are used for storage. While the hydroxyl groups on this molecule may be somewhat polar, the molecule as whole is relatively insoluble and therefore hydrophobic.

10) 5 carbon sugar

This molecule is both polar and hydrophilic.

## 4.1/5.1 Test Your Understanding

A student, Mary, is given four samples and told they are lysine (an amino acid), lactose (a disaccharide), insulin (a protein hormone), and RNA. The samples are in test tubes marked 1, 2, 3, and 4, but Mary doesn't know which compound is in which tube. She is instructed to identify the contents of each tube.

a. In her first test, she tries to hydrolyze a portion of the contents of each tube. Hydrolysis occurs in all tubes except tube 3.

b. In Mary's next test, she finds that tubes 1, 2, and 3 are positive for nitrogen but only tube 2 gives a positive result for the presence of sulfur.

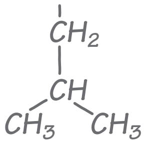
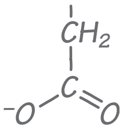
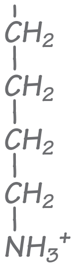
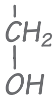
c. The last test Mary performs shows that the compound in tube 1 contains a high percentage of phosphate.

Based on these data, fill in the following table and explain your answers.

| Tube number | Contents | Explanation |
|---|---|---|
| 1 | RNA | Like DNA, RNA contains a sugar-phosphate backbone. |
| 2 | Insulin | Sulfur is a component of some amino acid side chains. It is not found in lysine, lactose, or RNA. |
| 3 | Lysine | All of the compounds except lysine are composed of macromolecular monomers joined by dehydration reactions. |
| 4 | Lactose | Since the contents of all the other tubes were determined in tests a to c, this tube must contain the lactose, a disaccharide. |

## Activity 4.2/5.2 What predictions can you make about the behavior of organic macromolecules if you know their structure?

1. Twenty amino acids are commonly utilized in the synthesis of proteins. These amino acids differ in the chemical properties of their side chains (also called R groups). What properties does each of the following R groups have? (*Note:* A side chain may display more than one of these properties.)

| R group | Basic, acidic, or neutral | Polar or nonpolar | Hydrophilic or hydrophobic |
|---|---|---|---|
| a.  | Neutral | Nonpolar | Hydrophobic |
| b.  | Acidic | Polar | Hydrophilic |
| c.  $CH_2CH_2CH_2CH_2NH_3^+$ | Basic | Polar | Hydrophilic |
| d.  $CH_2OH$ | Neutral | Polar | Hydrophilic |

2. Polypeptides and proteins are made up of linear sequences of amino acids. In its functional form, each protein has a specific three-dimensional structure or shape. Interactions among the individual amino acids and their side chains play a major role in determining this shape.

   a. How are amino acids linked together to form polypeptides or proteins? What is this type of bond called?

   Amino acids are covalently linked together via peptide bonds to form polypeptides or proteins. (See Figure 5.18 in *Campbell Biology*, 11th edition.)

| b. Define the four structures of a protein. | c. What kinds of bonds hold each of these structures together? |
|---|---|
| Primary:<br>The linear sequence of amino acids in a polypeptide or protein | Covalent peptide bonds formed by dehydration reactions hold the individual amino acids together in the polypeptide chain. |
| Secondary:<br>α helix or β pleated sheet conformations occurring at regular intervals along the polypeptide | The secondary structure results from H bonding relationships set up between the H attached to the N in one amino acid and the O attached to the C of another amino acid. |
| Tertiary:<br>The folded or functional conformation of a protein | Hydrogen and covalent bonds between side chains (R groups) of various amino acids contribute, as do hydrophobic interactions and van der Waals interactions. |
| Quaternary:<br>The folded or functional conformation of a protein made up of more than one polypeptide chain | Hydrogen and covalent bonds between side chains (R groups) of various amino acids contribute, as do hydrophobic interactions and van der Waals interactions. |

3. Lipids as a group are defined as being hydrophobic, or insoluble in water. As a result, this group includes a fairly wide range of compounds—for example, fats, oils, waxes, and steroids like cholesterol.

   a. How are fatty acids and glycerol linked together to form fats (triglycerides)?

   Dehydration reactions between the OH of the carboxyl group on the fatty acid and the OH group on the glycerol molecule bond the fatty acids to the glycerol molecules.

   b. What functions do fats serve in living organisms?

   In general, fats are energy storage molecules.

c. How do phospholipids differ from triglycerides?

Phospholipids have one of the OH groups of the glycerol interacting with a phosphate-containing side group—for example, phosphatidylcholine as in Figure 5.11.

d. What characteristics do phospholipids have that triglycerides do not have?

Phospholipids are amphipathic because the phosphate-containing side group is hydrophilic and the remainder of the molecule is hydrophobic. Triglycerides are hydrophobic.

## 4.2/5.2 Test Your Understanding

Use your understanding of the chemical characteristics of the four major types of macromolecules in living organisms to predict the outcome of the following experiments. Be sure to explain your reasoning.

**Experiment 1:** You stir 10 g of glucose and 10 mL of phospholipids in a 500-mL beaker that contains 200 mL of distilled water. Draw a diagram to show where and how the glucose and phospholipids would be distributed after you let the mixture settle for about 30 minutes.

The 10 g of glucose will dissolve in the water and be relatively evenly distributed in the water. The phospholipids will float on the surface of the water. The phospholipids at the water interface will have their hydrophilic phosphate heads in the water and their hydrophobic tails sticking out of the water. Any phospholipids trapped under the water may form micelles, with their fatty acid tails on the interior and their phospholipid heads pointing outward. It is possible that some of the phospholipids will form bilayers, which organize themselves into spheres containing small amounts of water.

**Experiment 2:** You repeat Experiment 1 again, but this time you stir 10 g of glucose and 10 mL of phospholipids in a different 500-mL beaker that contains 200 mL of distilled water and 100 mL of oil. Draw a diagram to show where and how the glucose, phospholipids, and oil would be distributed after you let the solution settle for about 30 minutes.

As in Experiment 1, the 10 g of glucose will dissolve in the water and be relatively evenly distributed in the water. Depending on how vigorously the system is mixed, the phospholipids may still float on the surface of the water. The phospholipids at the water interface will have their hydrophilic phosphate heads in the water and their hydrophobic tails associated with the oil layer above the water. Any phospholipids trapped under the water may form micelles, with their fatty acid tails on the interior and their phospholipid heads pointing outward. It is possible that some of the phospholipids will form bilayers, which organize themselves into spheres containing small amounts of water. Any phospholipids trapped in the oil layer may form inverted micelles, with their hydrophilic heads interior and their hydrophobic tails on the surface.

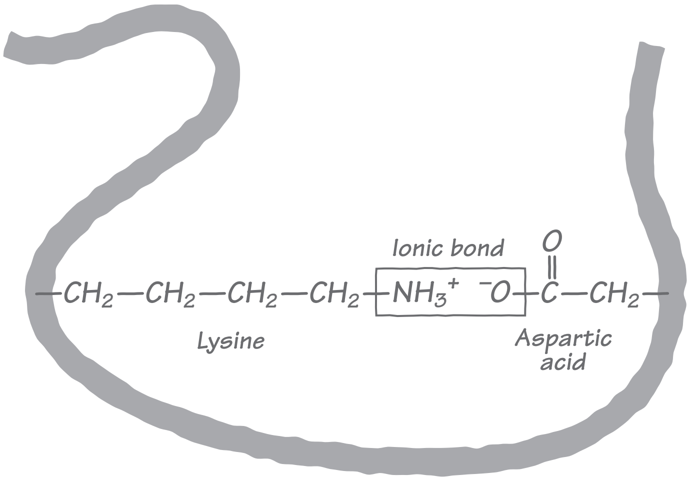
**Experiment 3:** To completely fill a sealed 500-mL glass container that contains 490 mL of distilled water, you inject 10 mL of phospholipids into it. (A small gasket allows the air to leave as you inject the phospholipids.) You shake this mixture vigorously and then let it settle for an hour or more. Draw a diagram to show how the phospholipids would be distributed in the container.

Under these circumstances, only micelles (and some phospholipid bilayer spheres) are likely to form.

**Experiment 4:** A globular protein that is ordinarily found in an aqueous solution has these amino acids in its primary structure: glutamic acid, lysine, leucine, and tryptophan. Predict where you would find each amino acid: in the interior portion of the protein (away from water) or on the outside of the protein (facing water). (Refer to Figure 5.16.)

Glutamic acid and lysine are electrically charged and will therefore be on the outside of the protein. Leucine and tryptophan are nonpolar and will be inside the protein.

**Experiment 5:** Drawn below is part of the tertiary structure of a protein showing the positions of two amino acids (aspartic acid and lysine). Replacing lysine with another amino acid in the protein may change the shape and function of the protein. Replacing lysine with which type(s) of amino acid(s) would lead to the least amount of change in the tertiary structure of this protein? (Refer to Figure 5.16.)



Aspartic acid has a negatively charged R group. Lysine has a positively charged side group. To cause the least amount of change in the tertiary structure of this protein, you have to replace lysine with an amino acid that contains a positively charged side group, such as arginine or histidine.

# Notes to Instructors

## Chapter 6  A Tour of the Cell

## What is the focus of this activity?

Students sometimes think that introductory biology texts and courses spend too much time dealing with cellular structure and function. It helps to remind them that many species of organisms (probably most species) exist only as single cells. Even complex multicellular organisms such as oak trees and humans start their lives as single-celled zygotes. In other words, all the characteristics of life can be found in single cells.

Considering the complexity of some multicellular organisms, how is this possible? How do prokaryotes such as heterotrophic bacteria eat? Why are all multicellular organisms eukaryotic? How can liver and nerve cells perform such different functions? How can different organelles in a cell contain different levels or concentrations of specific ions and other chemicals? Questions like these, and many others, cannot be answered without an understanding of basic cell structure and function.

## What is the particular activity designed to do?

**Activity 6.1  What makes a cell a living organism?**
The specific questions in this activity are designed to help students review and understand:

- the minimum structures or components a cell must contain to be alive,
- the function(s) of each part of the cell and how the function(s) is/are related to its structure, and
- the relative sizes of cellular structures or components.

## What misconceptions or difficulties can this activity reveal?

**Activity 6.1**
Question 2: In general, students understand that animal cells contain mitochondria. Yet, many think that plant cells differ from animal cells because they contain chloroplasts instead of mitochondria. It helps to remind students that plant cells contain both mitochondria and chloroplasts. It is even more effective, however, to ask them how plants make ATP at night, or how root cells, which cannot photosynthesize, make ATP.

Given these questions, most students will understand that plants must use ATP even in the dark. Some students don’t understand why this is a problem, however, because they think that ATP can be stored in the cells for use during periods when the plant is not photosynthesizing. As a result, you may need to let students know that ATP is not an energy storage molecule. Instead, plants produce sugars (which are converted to macromolecules such as starches) for long-term energy storage.

Question 3: Most students understand that a micrometer is one-millionth of a meter and a nanometer is one-billionth of a meter. However, they still may not have a good feel for the relative sizes of molecules and organelles in the cell. This question is designed to give students a better understanding of these relative sizes and help them understand how so many different chemical reactions can occur simultaneously inside a cell.

# Answers

## Activity 6.1 What makes a cell a living organism?

1. Single-celled organisms and individual cells within multicellular organisms can vary greatly in appearance as well as in the functions they perform. Nonetheless, each of these cells is alive and therefore must have some common characteristics.

| a. At a minimum, what structures or components must a cell contain to be alive? | b. What is the function of each structure or component listed in part a? |
|---|---|
| 1. Plasma or cell membrane | 1. A selectively permeable cell membrane allows the cell to control what enters and exits the cell. |
| 2. DNA | 2. DNA contains the genetic information for the production of all the macromolecules required by the cell—for example, enzymes, carbohydrates, structural proteins, etc. |
| 3. Ribosomes | 3. Ribosomes are required for the translation of proteins from mRNA. |

c. If you consider the types of single-celled organisms that exist today, which, if any, have a structure similar to your description in part a?

Many members of the prokaryotes have a structure similar to that described in part a.

2. What would you need to add to or change about the cell you described in question 1 to make it:

| a. A eukaryotic animal cell? | b. A eukaryotic plant cell? |
|---|---|
| 1. Double-membrane-bound nucleus containing chromosomes complexed with histone proteins.<br>2. Double-membrane-bound mitochondria for use in aerobic cellular respiration.<br>3. Cytoskeleton.<br>4. Endoplasmic reticulum and Golgi apparatus.<br>5. Centrosome for microtubule and spindle production. In animal cells, the centrosome contains a pair of centrioles.<br>6. Peroxisomes for a variety of functions, including generating hydrogen peroxide from oxygen and degrading it to water.<br>7. Lysosomes for intracellular digestion of macromolecules | 1. Double-membrane-bound nucleus containing chromosomes complexed with histone proteins.<br>2. Double-membrane-bound mitochondria for use in aerobic cellular respiration.<br>3. Cytoskeleton.<br>4. Endoplasmic reticulum and Golgi apparatus.<br>5. Microtubule organizing center (MTOC) for microtubule and spindle production. In general, plants do not have centrioles. Only a few cell types (e.g., ferns and gymnosperms) develop centrioles.<br>6. Peroxisomes for a variety of functions, including generating hydrogen peroxide from oxygen and degrading it to water.<br>7. Double-membrane-bound chloroplasts for photosynthesis.<br>8. Central vacuole for storage and for breakdown of waste products.<br>9. Cell wall.<br>10. Plasmodesmata, which are connections of cytoplasm from one cell to the next. |

3. To get an idea of the different sizes of various cellular components, do the following calculations: Assume that the cell, its nucleus, and a globular protein—for example, an enzyme—are spherical. In addition, assume the diameter of the protein is 5 nm, the diameter of the cell is 100 μm (micrometers), and the diameter of the nucleus is 40 μm.

| If you draw the globular protein as a sphere with a diameter of 2 cm (approximately the diameter of a U.S. penny), what size would each of the following measurements of the cell be if drawn to the same scale (5-nm real length = 2 cm)? | |
|---|---|
| a. The radius of a microtubule (Refer to Table 6.1 in *Campbell Biology,* 11th ed.) | If 5 nm = 2 cm, then 1 nm = 0.4 cm. Radius of microtubule = 25 nm = 25 × 0.4 cm = 10 cm. |
| b. The diameter of the nucleus | 40 μm = 40,000 nm × 0.4 cm/nm = 160 m (A football field is 100 yards long, or about 91.4 m.) |
| c. The diameter of the cell | 100 μm = 100,000 nm × 0.4 cm/nm = 400 m |
| d. The volume ($V = 4/3\ \pi r^3$) of the protein 1 nanometer cubed (1 nm$^3$) = $1.0 \times 10^{-21}$ centimeters cubed (cm$^3$). | $4/3\ \pi\ (1\ \text{cm})^3 = 4.2\ \text{cm}^3$ |
| e. The volume of the nucleus | $4/3\ \pi\ (80\ \text{m})^3 = 2.1 \times 10^6\ \text{m}^3$ |
| f. The volume of the cell | $4/3\ \pi\ (200\ \text{m})^3 = 3.4 \times 10^7\ \text{m}^3$ |

g. The volume of the Empire State Building is $1.05 \times 106\ \text{m}^3$. How many of your scaled nuclei could fit into the Empire State Building? How many of your scaled cells could fit?

The volume of the scaled nucleus is almost 2 times the volume of the Empire State Building and the cell volume is about 20 times greater.

h. Do the results of these calculations help you to understand how so much can be going on inside a cell at once? Explain.

The calculations give a clearer idea of dimension relationships inside cells. For example, if a single protein molecule is only about 2 cm in diameter, 20,000 protein molecules of this size could be lined up along the diameter of the cell (400 m).

# Notes to Instructors

## Chapter 7 Membrane Structure and Function

### What is the focus of these activities?

To be alive and to continue to survive in changing environments, organisms must be able to keep their integrity separate from the environment and other organisms.

In Activity 6.1, students reviewed the cell as the basic unit of life. In the Chapter 7 activities, students review the functions of membranes that allow them to control the movement of substances into and out of the cells.

### What are the particular activities designed to do?

**Activity 7.1 What controls the movement of materials into and out of the cell?**
**Activity 7.2 How is the structure of a cell membrane related to its function?**

These activities are designed to help students begin to understand:

- the physical and chemical factors that affect the transport of substances into and out of cells (as well as into and out of organelles), and
- how the size of solute molecules affects osmotic potential.

### What misconceptions or difficulties can these activities reveal?

**Activity 7.1**
Question 1: Many students visualize the phospholipid bilayer as a static structure rather than as a fluid structure. As a result, they have a difficult time understanding how anything could move across a membrane made of phospholipids alone.

The difficulty understanding the fluid nature of membranes isn't that surprising. After all, how does something that is fluid act as a boundary layer? If it is so fluid, why do red blood cells in hypotonic solution swell so much before they burst or lyse? Why don't the membranes just separate into individual phospholipid units under this pressure? Many of us have similar difficulty understanding how various chemical elements can be solid or dense when each atom is composed of electrons orbiting around a central core of protons and neutrons.

Although it doesn't answer these questions, it helps to remind students of the size differences that exist among cells, phospholipids, and the substances that can move through them. For example, a molecule of oxygen, carbon dioxide, or water is at least 50 times smaller than a phospholipid molecule. In addition, the distances that individual phospholipid molecules move per unit time are very small. For example, *Campbell Biology*, 11th edition, notes that phospholipids can move about 2 μm/second. In comparison, the diffusion rate for substances in water is about 40 μm/second. This means that the movement of phospholipids in the membrane is about 20 times slower than the movement of water molecules in diffusion. In other words, phospholipid membranes are fluid but nowhere near as fluid as water.

Question 2: Many students don't understand how molecular size affects osmotic potential. Once they understand this, it will be easier for them to understand why systems don't store ATP or sugar molecules, but instead store energy in the form of starches and fats.

**Activity 7.2**
Modeling the different types of transport as they occur in a single membrane allows students to recognize that all three types of transport can be going on simultaneously in different parts of the membrane.

# Answers

## Activity 7.1 What controls the movement of materials into and out of the cell?

1. To be alive, most cells must maintain a relatively constant internal environment. To do this, they must be able to control the movement of materials into and out of the cell.

   What characteristics of the cell membrane determine what does and what does not get into the cell? That is, what determines the permeability of a cell or organelle membrane? To answer these questions, first consider the answers to the following questions:

| a. If a cell membrane were composed of only a phospholipid bilayer, what properties would it have? | b. What different roles or functions do membrane proteins serve? | c. Why are some cell types more permeable to a substance (for example, sodium ions) than others? |
|---|---|---|
| Phosopholipids contain a hydrophilic phosphate head region and a hydrophobic fatty acid tail region. When these form a bilayer, the phosphate heads interact with the water and the fatty acid tails interact with each other. If you think of this as a static, continuous structure, then it is easy to see that nothing should get through. Charged molecules should be repelled or attracted by the phospholipid head ends, and hydrophilic substances should be unable to cross the fatty acid region. However, this is not a static structure, so very small uncharged molecules and water can move across a phospholipid bilayer. | Membrane proteins allow charged and larger molecules to cross the membrane. They facilitate the passage of these molecules. As a result, diffusion of molecules through such membrane proteins is called facilitated diffusion. Other membrane proteins use the energy in ATP to move molecules across membranes against a concentration gradient.These types of membrane proteins are often called pumps and function in active transport. | The difference in permeability is the result of differences in the types of membrane proteins the cells contain. |

Using your understanding of the answers in a–c, now answer these questions: What characteristics of the cell membrane determine what does and what does not get into the cell? That is, what determines the permeability of a cell or organelle membrane?

Only very small uncharged or nonpolar molecules are capable of diffusing across the phospholipid bilayer. Specific membrane transport proteins are required for the movement of all other types of molecules into or out of the cell or organelle. Cells and organelles vary in the types of membrane transport proteins they contain. This variability is a function of which genes are active in each cell type.

2. You design an experiment to test the effect(s) various compounds have on the osmotic potential of a model cell. You know that substances dissolved in aqueous or gaseous solutions tend to diffuse from regions of higher concentration to regions of lower concentration.

You fill each of three (20-mL) dialysis bags half full with one of these substances:

- 5% by weight of glucose in distilled water
- 5% by weight of egg albumin (protein) in distilled water
- 5% by weight of glass bead (one glass bead) in distilled water

The dialysis bag is permeable to water but impermeable to glucose, albumin, and glass bead.

a. If the final weight of each bag is 10 g, how many grams of glucose, albumin, and glass bead were added to each bag?

Five percent of the weight in each bag is glucose, albumin, or glass bead. Therefore, each of these weighs 0.5 g.

b. The molecular weight of the protein is about 45 kilodaltons, and the molecular weight of glucose is about 180 daltons. How can you estimate the number of molecules of glucose in the 5% solution compared to the number of albumin molecules in its 5% solution?

Each molecule of protein is 45,000/180 (or 250) times heavier than each molecule of glucose. Therefore, if the weights of glucose and albumin are the same in each of the bags, there are about 250 times more molecules of glucose in 0.5 g than molecules of protein in 0.5 g.

c. You put the dialysis bags into three separate flasks of distilled water. After 2 hours, you remove the bags and record these weights:

| Dialysis bag | Weight |
|---|---|
| Glucose | 13.2 g |
| Albumin | 10.1 g |
| Glass bead | 10.0 g |

How do you explain these results? (*Hint:* Consider the molarity and the surface-area-to-volume ratio of each of the three substances and review Chapter 7 of *Campbell Biology*, 11th edition.)

Five grams of glucose equals 5g/180g/M = approximately 0.027 M of glucose. Five grams of albumin equals 5g/45,000g/M = approximately 0.00011M of albumin. In other words, 5 g of glucose contains many more molecules of solute than does 5 g of albumin. As a result, the 5 g of smaller glucose molecules have a much larger total surface area than the 5 g of albumin molecules. When molecules dissolve in water, water molecules form a ring of hydration around each of the solute molecules. The water in the ring of hydration in effect reduces the concentration of free water molecules in the solution (relative to the distilled water outside the bag). Free water then moves down its concentration gradient and enters the bag. Because the 5 grams of albumin have a much smaller surface area, much less water is required to form the rings of hydration around the albumin molecules. Therefore, there is a smaller difference in the concentrations of free water molecules inside versus outside the bag. When the concentration difference is smaller, less water enters the bag.

In contrast, the glass bead is insoluble in water. It can be thought of as one large "molecule." Therefore, its surface-area-to-volume ratio is much smaller than that of either the albumin or glucose. The amount of free water that is required to form the ring of hydration around the glass bead is very small relative to either albumin or glucose.

d. What results would you predict if you set up a similar experiment but used 5% glucose and 5% sucrose?

Glucose has a molecular weight of 180 daltons. Sucrose has a molecular weight of 342 daltons. Both would gain water, but the glucose solution would gain more water because, on average, a 5% glucose solution contains twice as many molecules as a 5% sucrose solution. In addition, each glucose molecule is smaller than each sucrose molecule, so its surface-area-to-volume ratio is higher.

## Activity 7.2 How is the structure of a cell membrane related to its function?

Membranes compartmentalize the different functions of living cells. The cell membrane is a barrier between the cell or organism and its environment. Similarly, within the cell, membranes of organelles separate the different reactions of metabolism from each other.

Use the supplies provided in class or devise your own at home to develop a model of a cell membrane. Developing models of systems can help you understand not only their overall structure but also their function(s).

## Building the Model

- Include in the membrane the phospholipid bilayer (phosphate heads and fatty acid tails) as well as the integral proteins.
- Design integral proteins that serve the functions of facilitated diffusion and active transport.
- Indicate how the various types of integral proteins might differ in structure and operation.

**Use the understanding you gain from your model to answer the following questions:**

1. Substances can move across the membrane via simple diffusion, facilitated diffusion, or active transport.

| | a. Where does it occur in the membrane? | b. Does it require transport protein? | c. Does it require input of energy? |
|---|---|---|---|
| Simple diffusion | Across the phospholipid bilayer | No | No |
| Facilitated diffusion | Through membrane proteins | Yes | No |
| Active transport | Through membrane proteins | Yes | Yes |

d. What functions might each of the three types of diffusion serve in an independent cell such as a *Paramecium* or an amoeba?

Many possible examples can be used to answer this. For example, water and oxygen could enter these cells via simple diffusion. Fatty acids, produced as a result of digestion in a food vacuole, may also be able to move across the vacuole membrane by simple diffusion. Other macromolecules are likely to be moved across the vacuole membrane via active transport or facilitated transport. Ions may move passively across membranes inside the cell or may be actively transported if concentration differences exist across membranes.

e. What functions might each of the three types of diffusion serve in a multicellular organism—for example, a human or a tree?

Again, many possible examples can be used here. For example, in humans and trees, various ion concentration gradients are set up via active transport. Water, oxygen, and carbon dioxide move across membranes via simple diffusion. Movement of some macromolecules, such as glucose, can occur via facilitated transport.

2. What would you need to observe or measure to determine whether a substance was moved across a membrane via each type of diffusion?

| Simple diffusion | Facilitated diffusion | Active transport |
|---|---|---|
| No energy required—that is, this can occur in absence of ATP.<br>Can be observed to occur across artificial phopholipid bilayer. | No energy required. Does not occur across a phospholipid bilayer alone. Occurs across a membrane containing appropriate membrane proteins. | Energy required. Occurs only across a membrane containing the appropriate membrane proteins. |

3. The ratios of saturated to unsaturated phospholipids in an organism's membranes can change in response to changes in environmental conditions.

   a. How do the properties of a membrane that contains a low percentage of unsaturated phospholipids compare with those of a membrane that contains a high percentage of unsaturated phospholipids?

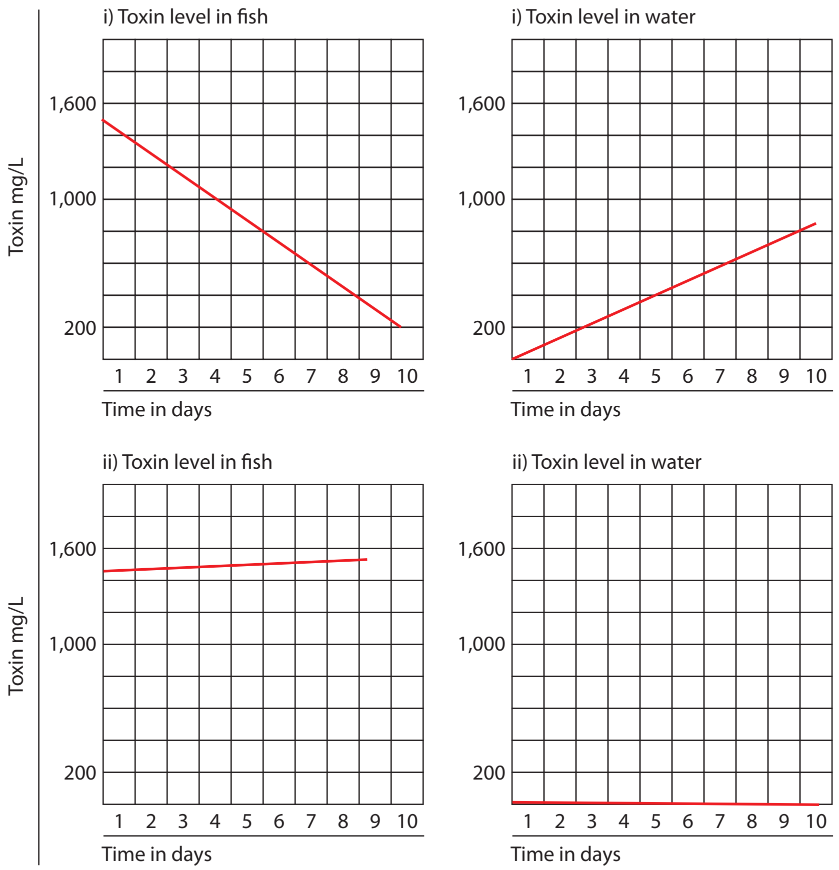
   Unsaturated phopholipids remain fluid at lower temperatures. Therefore, a membrane with a low percentage of unsaturated phospholipids is less fluid than one with a high percentage of unsaturated phospholipids.

   b. Considering what you know about the properties of saturated and unsaturated fatty acids, would you expect an amoeba that lives in a pond in a cold northern climate to have a higher or lower percentage of saturated fatty acids in its membranes during the summer as compared to the winter? Explain your answer.

   For the membranes to remain fluid in cold temperatures, they must contain a higher concentration of unsaturated phospholipids in the winter than in the summer. In the summer, increasing the concentration of saturated phospholipids would prevent the membrane from becoming too fluid. In fact, scientists have measured the percentage of saturated and unsaturated fatty acids in the membranes of the same organisms over the year and have noted that the composition changes to increase the percentage of unsaturated fatty acids in colder weather.

4. A fish is removed from a contaminated lake. You determine that a particular toxin (T) is present in its cells at concentration $T = 1500$ μg/L. You place the fish in a tank full of clean water ($T = 0$ μg/L), and measure the toxin concentration in the fish cells over the next 10 days.

a. On the graphs below, predict how the toxin concentrations in the fish and in the water will change over time if:
   i. the toxin is water soluble
   ii. the toxin is fat soluble



b. After making your hypothesis, you test it by measuring the toxin levels in the fish at various times during its 10 days in the tank. You observe that the level of toxin in the fish drops from 1,500 μg/L to 750 μg/L and then stabilizes at 750 μg/L. You test the water in the tank and find that after it stabilizes, toxin is present in the water at 750 μg/L also.

- Which of your predictions fit these data?

  The hypothesis that the toxin is water soluble fits the data.

- Which of the following processes is most likely eliminating the toxin from the fish?
  i. Passive transport
  ii. First active, then passive transport
  iii. First passive, then active transport
  iv. Active transport

  Because the levels inside and outside the fish become equal and stabilize there, the data support a passive transport mechanism alone.

c. Given the situation in part b, what should you do, in the short term, to continue to reduce the toxin level in the fish below 750 μg/L?

The easiest method would be to continue to change the water on a daily basis. Each time the water is changed, the concentration of X outside the fish is lower than inside. As a result, X will tend to move from the region of higher concentration (in the fish cells) to lower concentration in the surrounding water.

5. A particular amino acid is transported from the extracellular medium against its concentration gradient. The integral membrane protein that transports the amino acid also binds and transports $Na^+$. Using your model of the cell membrane, develop a transport mechanism that will permit the amino acid uptake to be coupled to the $Na^+$ transport so that the amino acid's entry is linked only indirectly to ATP hydrolysis.

   This situation is similar to the one diagrammed in Figure 7.18.

# Notes to Instructors

## Chapter 8  An Introduction to Metabolism

## What is the focus of these activities?

Many students study biology as if it were a foreign language. For them, each new topic or idea is distilled into separate definitions. Each is then written on a flash card to be memorized. This approach to studying biology has obvious limitations; the biggest is that it does not require students to make connections and integrate their understanding. Activity 8.1 requires students to integrate information from Chapter 8 on general metabolism and enzyme function with what they learned about protein structure in Chapter 5. Activity 8.2 has them apply their understanding to propose how differences in experimental conditions could affect reaction rates and to analyze the results of some simple experiments in enzyme function.

## What are the particular activities designed to do?

### Activity 8.1  What factors affect chemical reaction in cells?

This activity asks the students to construct a concept map that integrates their understanding of protein structure, enzyme function, and general energy transformations in metabolic reactions. This requires that they have a general understanding of enzyme structure and function.

### Activity 8.2  How can changes in experimental conditions affect enzyme-mediated reactions?

This activity asks students to apply their general understanding from Activity 8.1 to specific experimental situations. They must understand how enzyme function (and therefore metabolism) can be affected by changes in substrate and/or product concentration and by changes in the enzyme itself.

## What misconceptions or difficulties can these activities reveal?

### Activity 8.1

If done in small groups in class, the concept mapping activity can be used to reveal both the students' levels of understanding and any misconceptions they may have. Doing this activity helps many students understand how the tertiary (or quaternary) structure of an enzyme can be modified by modifying a side group on an amino acid. In addition, understanding the impact of changes in the physical or chemical conditions surrounding the enzyme can help students understand why organisms expend so much energy maintaining homeostasis.

Question 1: Because they tend to memorize terms and definitions separately, many students don’t recognize that a single reaction can simultaneously be spontaneous, catabolic, and exergonic and have a negative $\Delta G$.

Question 2: For years the dogma held that all enzymes were proteins. This question can be used to point out that we now know that some enzymes are made of RNA.

Question 3: This question points out the types of factors that can affect enzyme function. Students need to make the logical leap that for cells to maintain their metabolism at optimal levels, they must be able to regulate their internal environment. Many students do not make this connection without additional help or suggestions.

**Activity 8.2**

This set of experimental situations gives students practice in making the connection between “knowing something” (for example, knowing the definitions of competitive and noncompetitive inhibitors) and understanding how to use that information to interpret results or to predict results if their understanding is correct. Many students are not comfortable doing this, especially in situations that have more than one possible answer depending on the assumptions the student makes. Therefore, these questions give them practice with developing both assumptions and predictions based on those assumptions.

# Answers

## Activity 8.1 What factors affect chemical reactions in cells?

Construct a concept map of general metabolism using the terms on the following page. Keep in mind that there are many ways to construct a concept map.

- Begin by writing each term on a separate sticky note or piece of paper.
- Then organize the terms into a map that indicates how the terms are associated or related.
- Draw lines between terms and add action phrases to the lines to indicate how the terms are related.
- If you are doing this activity in small groups in class, explain your map to another group when you finish it.

Here is an example:

## Terms

peptide bonds
proteins
α helix
primary structure
secondary structure
tertiary structure
β pleated sheet
R groups
hydrogen bonds
substrate or reactant (ligand)

activation energy
ΔG / free energy
endergonic
exergonic
enzymes
catalysts
competitive inhibitor
noncompetitive inhibitor
active site
product
allosteric regulation

activator
four-step enzyme-mediated reaction sequence or metabolic pathway ($A \rightarrow B \rightarrow C \rightarrow D$)
intermediate compound
end product
feedback inhibition

**Use the understanding you gained from doing the concept map to answer the questions.**

1. Reduced organic compounds tend to contain stored energy in C—H bonds. As a general rule, the greater the number of C—H bonds, the greater the amount of potential energy stored in the molecule. Answer each question in the chart as it relates to the two reactions shown at the top. Be sure to explain the reasoning behind your answers.

| | Reaction 1:<br>$CH_4 + 2\ O_2 \rightarrow H_2O + CO_2$<br>(methane) | Reaction 2:<br>$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$ |
|---|---|---|
| a. Is the reaction exergonic or endergonic? | Exergonic<br>This reaction releases energy. | Endergonic<br>This reaction requires energy. |
| b. Is the reaction spontaneous? | Yes<br>The end products are at lower energy levels than the reactants. | No<br>The end products are at higher energy levels than the reactants. |
| c. Is the reaction anabolic or catabolic? | Catabolic<br>This reaction "breaks down" methane into water and carbon dioxide. | Anabolic<br>This is a synthetic reaction that "builds up" sugar from water and carbon dioxide. |
| d. Is ΔG (the change in free energy) positive or negative? | Negative<br>Free energy is released. | Positive<br>The reaction requires the input of free energy. |

2. All metabolic reactions in living organisms are enzyme mediated. Each enzyme is specific for one (or only a very few similar types of) reaction. Given this, there are approximately as many different kinds of enzymes as there are reactions.

   a. What characteristics do all enzymes share?

   All enzymes contain a reactive site. All have a specific conformation that fits them to their substrate(s). All serve to reduce the activation energy of reactions.

   b. What characteristics can differ among enzymes?

   Before ribozymes were discovered, we thought that all enzymes were composed of protein. Now we recognize that some RNAs also are catalytic. Some protein enzymes include cofactors, which can be ions or other organic compounds. If a cofactor is organic, it is called a coenzyme. Many vitamins are coenzymes.

3. How can enzyme function be mediated or modified? To answer, complete a and b below.

| a. What factors can modify enzyme function? | b. What effect(s) can each of these factors have on enzyme function? |
|---|---|
| Among other factors, the temperature and pH at which an enzyme is active can vary. | Each enzyme has a range of temperatures in which it functions. (Refer to Figure 8.17.)<br>The same is true for pH. At temperatures and pHs outside this range, protein enzymes can become denatured. This changes their 3-D configuration and therefore their ability to function. |
| In addition, various enzymes may be inhibited or activated by different factors. | The action of some enzymes can be inhibited by molecules that compete for the active site (competitive inhibition). Other inhibitors can bind at another site and alter the configuration of the active site (noncompetitive inhibition). (See Figure 8.18.)<br>In some cases, activators are required to stabilize the active 3-D form of the enzyme. (See Figure 8.20.) |

c. What role(s) can modification of enzyme function play in the cell?

To maintain optimal levels of enzyme activity and therefore metabolism, cells must maintain a relatively constant internal environment (homeostasis). On the other hand, cells can control or modify enzyme function to inhibit or enhance the function of a specific enzyme (as noted in part b). As a result, cells can maintain tight control over the levels of various cellular components. For example, an end product of a reaction series can serve as an allosteric inhibitor of the first enzyme in the pathway. This type of control has the effect of quickly and efficiently turning off the entire pathway when the end product occurs in excess (or of turning it on when the end product concentration decreases).

## Activity 8.2 How can changes in experimental conditions affect enzyme-mediated reactions?

1. You set up a series of experiments to monitor the rates of a reaction. The reaction is an enzyme-mediated reaction in which $A \rightarrow B + C$. For each experiment in this series, you continuously add the reactant A and monitor its concentration so that the amount of A remains constant over time.

For each group of experiments, explain how the differences in experimental conditions could affect the reaction.

a. You compare two side-by-side experiments. In experiment 1, you use *X* amount of the enzyme. In experiment 2, you use 2*X* amount of the same enzyme.

If you double the amount of enzyme present, you double the rate of accumulation of the product. The rate at which any specific enzyme operates to make $A \rightarrow B + C$ does not change. However, the rate at which C accumulates appears to double. For example, if one enzyme can complete the reaction $A \rightarrow B + C$ in 1 msec, then at the end of 1,000 msec (1 second) we would expect 1,000 A to be converted to 1,000 B + 1,000 C. If two enzymes were working simultaneously, then within 1 second, 2,000 A could be converted to 2,000 B + 2,000 C. (*Note*: This answer assumes that the amount of A is much greater than the amount of B + C.)

b. You compare two side-by-side experiments. In both you use equal amounts of the enzyme. In experiment 3, you allow the products to accumulate over time. In experiment 4, you remove the products from the system as they are produced.

Recall that most metabolic reactions are reversible, and for these reactions, the same enzyme that catalyzes the forward reaction can generally catalyze the reverse reaction. As a result, in experiment 4, the apparent rate of the reaction will be constant over time. In other words, to use the example above, each enzyme will break down a unit of A into B and C every millisecond. In experiment 3, however, as the reaction reaches equilibrium levels of A versus B + C, the apparent rate of the reaction will decrease. Each enzyme will still be operating at the same rate (1 reaction per millisecond); however, some will be catalyzing the forward reaction and some the reverse reaction. At equilibrium, the numbers of enzyme molecules catalyzing the forward versus reverse reactions per unit time should be equal.

c. In the next two experiments, you use equal amounts of the enzyme. You run experiment 5 at 20°C and experiment 6 at 25°C.

As noted in Figure 8.17, each type of enzyme is functional within a set range of temperatures. The temperature at which the enzyme has its greatest rate of activity or reaction rate is called its *optimal temperature*. On either side of the optimal temperature (positive or negative), the rate of the enzyme-catalyzed reaction decreases. As a result, exactly how the enzyme in this system will react depends on both its optimal temperature and the range of temperatures over which it is active. For example, if we assume the enzyme's range of temperature is 0°C to 50°C and its optimal temperature is about 35°C, then the rate at which the enzyme works at 25°C will be faster than its rate at 20°C. On the other hand, if the range of temperatures for this enzyme is 40° to 90°C, then at both 20° and 25°C, we will see no activity.

d. In two final experiments, you use equal amounts of the enzyme. You run experiment 7 at pH 6 and experiment 8 at pH 8.

Similar to part c, each enzyme has an optimal pH and a range of pH in which it is active. As above, exactly how the enzyme will react at pH 6 versus pH 8 will depend on its optimal pH and range of pH.

2. Enzyme function can be inhibited or regulated by the presence of chemicals that mimic either the reactants or the products.

a. How do competitive and noncompetitive inhibition of an enzyme differ?

Refer to Figure 8.18. A competitive inhibitor can bind at the active site of an enzyme and prevent the substrate from binding. A noncompetitive inhibitor binds at a different site on the enzyme and changes the shape of the active site, which then prevents the substrate from binding.

b. What are allosteric enzymes? What function(s) can they serve in reaction sequences?

Refer to Figure 8.20. Allosteric enzymes are usually made up of more than one polypeptide. The activity of these enzymes is often controlled by enhancers and inhibitors, which bind at different sites on the enzyme. Binding of an enhancer changes the enzyme's shape and makes its active site(s) available for catalysis. Binding of an inhibitor also causes a shape change, but one that makes the active site(s) unavailable.

3. An enzyme catalyzes the reaction $X \rightarrow Y + Z$. In a series of experiments, it was found that substance A inhibits the enzyme.

   - When the concentration of X is high and A is low, the reaction proceeds rapidly and Y and Z are formed.
   - As the concentration of A increases, the reaction slows regardless of whether X is present in high or low concentration.
   - If the concentration of A is high (relative to X), the reaction stops.
   - If the concentration of A again decreases, the reaction will ultimately resume.

   What type of enzyme regulation is described here? Explain or justify your answer.

   The enzyme in the reaction described, $X \rightarrow Y + Z$, is most likely an enzyme that has a site for a noncompetitive inhibitor molecule. If this were a case of competitive inhibition, then the higher the concentration of X (relative to A), the faster the reaction rate should be. The inhibition described is also reversible, as evidenced by the ability of the reaction to resume if the concentration of A decreases.

4. In an enzymatic pathway, A, B, and C are intermediates required to make D; and 1, 2, and 3 are enzymes that catalyze the designated reactions:

$$\begin{tikzcd} A \arrow[r, "1"] \arrow[d] & B \arrow[r, "2"] & C \arrow[r, "3"] & D \\ E & & & \end{tikzcd}$$

   This is analogous to what happens in a factory. In a leather goods factory, for example, the leather (A) is cut (1) into the parts needed for shoes (B). The shoe parts are sewn (2) together (making C), and C is packaged (3) for shipping as D. Now shoe sales are dropping and backpack sales (E) are increasing. As a result, the manager of the factory decides to switch production from shoes to leather backpacks (E).

   a. Where should the shoe-making process be shut down: step 1, 2, or 3? Explain.

      The shoe-making process should be shut down at step 1. It makes no sense to produce any of the parts to make shoes if you don't need them.

   b. In a cell, if an excess of a chemical product D arises, where should this synthetic pathway be shut down in the cell?

      If we use the same logic as in part a, then the synthetic pathway $A \rightarrow B \rightarrow C \rightarrow D$ should also be shut down at the first step.

   c. What type(s) of enzyme regulation is/are most likely to occur in the cell in this type of feedback system? Explain your reasoning.

      Allosteric enzymes are frequently involved in this type of feedback regulation of synthetic pathways.

# Notes to Instructors

## Chapter 9 Cellular Respiration: Harvesting Chemical Energy
## Chapter 10 Photosynthesis

### What is the focus of these activities?

In studying both cellular respiration and photosynthesis, many students tend to focus on the details and miss the big picture. They can recite specific reactions that occur in glycolysis and the Krebs cycle, for example, but they don't understand the overall purpose of these parts of the process. These activities are designed to help students understand the overall purpose of each process and how these processes are interrelated evolutionarily.

### What are the particular activities designed to do?

**Activity 9.1 A Quick Review of Energy Transformations**
This activity adds consideration of the terms *oxidation* and *reduction* to the energy relationships students learned in Chapter 8.

**Activity 9.2 Modeling Cellular Respiration**
Activity 9.2 is designed to help students understand:

- the overall functions of glycolysis, the Krebs cycle, and oxidative phosphorylation;
- how fermentation allows organisms to survive periods of low or no oxygen; and
- how the potential energy in a hydrogen ion concentration gradient can be used to generate ATP in oxidative phosphorylation.

**Activity 10.1 Modeling Photosynthesis**

**Activity 10.2 How do $C_3$, $C_4$, and CAM photosynthesis compare?**

Activities 10.1 and 10.2 are designed to help students understand:

- the roles photosystems I and II and the Calvin cycle play in photosynthesis, and
- how and why $C_4$ and CAM photosynthesis differ from $C_3$ photosynthesis.

### What misconceptions or difficulties can these activities reveal?

**Activity 9.1**
This activity reviews the information presented in Chapter 8 and helps students integrate into that an understanding of oxidation and reduction reactions that occur in living organisms.

## Activity 9.2

By doing this modeling exercise, students will not only learn the definitions of all the terms and structures involved in cellular respiration but also get an understanding of how they function or interact in the cell.

Many students don’t understand what they do and, more important, don’t know about the processes of cellular respiration. When students build this kind of visual claymation model, what they don’t know becomes apparent and they have reason to “fill in the blanks.” Visualizing the processes using a model they build for themselves generally leads to a better and more complete understanding.

Question 1: To help give students the “big picture,” this question looks at the summary formula for cellular respiration and asks where each reactant is used and where each product is produced in the process. Many students have difficulty answering most parts of this question.

Questions 2 and 3: The same observation applies to these questions. Many students concentrate on the details of reactions and don’t appear to understand the overall purpose of each part of the process. These questions are designed to help them put the pieces together.

Questions 4, 5, and 6: These questions examine what happens in aerobic cellular respiration when oxygen and, therefore, $NAD^+$ become limiting. We generally teach the various processes of cellular respiration in order from glycolysis to the Krebs cycle to electron transport and oxidative phosphorylation. Many students get the mistaken impression that they must operate in this sort of relay fashion in the cell as well. Only a few introductory students understand that all of these processes are occurring simultaneously in the cell. Fewer yet have a good idea that various molecules and resources in the cell (for example, $NAD^+$) are finite and can be limiting. And it is the rare student who can answer the question: Why does the Krebs cycle stop in the absence of oxygen if oxygen is not required in the Krebs cycle? We hope these questions will help students understand this and the relationships among these processes.

Question 7: This question gives students practice with the concept of energy efficiency and methods of calculating it, both of which are difficult for some students.

Question 8: Students know that ATP is the “energy currency” of the cell. However, few understand why organisms store energy as starch, fats, or oils instead of as ATP. Students must integrate an understanding of osmotic relationships from Chapter 3 with an understanding of the structure and function of ATP in order to answer this question.

Question 9: When chemiosmosis is discussed, students are asked to understand that a hydrogen ion concentration gradient has potential energy that can be used to do work—in this case, to drive the synthesis of ATP. The operation of a battery is often used as an example; however, few students seem to understand how batteries work. We provide the example of mixing concentrated acid with water, which can be done in class (under strict supervision) to demonstrate how establishing (and releasing) a hydrogen ion concentration gradient can generate energy (in this case, heat).

Questions 10 and 11: These questions ask students to apply what they have learned about molar equivalents (Chapter 2) to solve simple problems in cellular respiration.

Question 12: This question asks why living organisms don't spontaneously combust. Students should be able to understand this if they understand the process of cellular respiration.

**Activity 10.1**

Students have the same difficulties understanding photosynthesis that they have understanding cellular respiration. This activity asks students to model photosynthesis in the chloroplast. Its design and purpose are parallel to those for the cellular respiration modeling activity (Activity 9.2). By building their own model of photosynthesis, students will not only learn the definitions of all the terms and structures involved but also get an understanding of how they function or interact in the cell. More important, students will discover what they don't know or don't understand and then remedy the problem.

Questions 1, 2, and 3: As in Activity 9.2, these questions are designed to help students develop the big picture and get a good understanding of the overall purpose of each process.

Question 4: Whereas Activity 9.2 looked at what happens when $NAD^+$ becomes limiting in cellular respiration, this question looks at what happens when $NADP^+$ becomes limiting in photosynthesis.

Question 5: The question of why plants need to make glucose and store starch as an energy source is addressed. Many students don't understand why plants can't just use the ATP directly for processes other than photosynthesis. In fact, they can, as long as they are making excess ATP. When there is little or no sunlight, however, ATP production via photophosphorylation is reduced or halted entirely.

In addition, most students don't understand that the three-carbon compounds produced in the Krebs cycle are not all used to make glucose. All the organic compounds produced by plants use these (or modifications of these) as precursors.

**Activity 10.2**

Question 1: This question is set up to allow students to more easily compare, and therefore learn, the similarities and differences among $C_3$, $C_4$, and CAM photosynthesis.

Question 2: Many students have difficulty understanding how rubisco can serve as both a carboxylase and an oxidase. This becomes easier to understand when students recognize that rubisco probably arose as a mutation in organisms when the early Earth's atmosphere was anaerobic.

Question 3: This question asks students to develop an evolutionary scheme for glycolysis, the Krebs cycle, oxidative phosphorylation or electron transport, and photosynthesis. Many students have the misconception that the order in which the processes were presented either in lecture or in the text is the order in which they evolved. This will be obvious in their answer to this question. Fewer students will automatically use what they know about each process—for example, what each process requires—to develop a logical scheme of evolution.

# Answers

## Activity 9.1 A Quick Review of Energy Transformations

**Review Chapters 8 and 9 in *Campbell Biology*, 11th edition. Then complete the discussion by supplying or choosing the appropriate terms.**

To maintain life, organisms must be able to convert energy from one form to another. For example, in the process of photosynthesis, algae, plants, and photosynthetic prokaryotes use the energy from sunlight to convert carbon dioxide and water to glucose and oxygen (a waste product).

The summary reaction for photosynthesis can be written as:

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

This type of reaction is an oxidation-reduction (or redox) reaction. This reaction is also [***anabolic*****/catabolic**] and [***endergonic*****/exergonic**].

In redox reactions, **electrons** (and associated $H^+$ ions) are transferred from one compound or element to another. If one compound or element "loses" **electrons** and becomes oxidized, another must "gain" **electrons** and become reduced. For example, in photosynthesis, water becomes [***oxidized*****/reduced**] (to $O_2$) and the **electrons** (and associated $H^+$ ions) it loses in the process [**oxidize/*reduce***] $CO_2$ to glucose.

[***Anabolic*****/Catabolic**] reactions "build" more complex molecules from simpler ones. To do this they require energy input. Reactions that require the input of energy are termed [***endergonic*****/exergonic**] reactions.

The reactions involved in aerobic respiration are also redox reactions:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

In this set of reactions, however, more complex molecules are "broken down" into simpler ones. Glucose is broken down or becomes [***oxidized*****/reduced**] (to $CO_2$), and the oxygen becomes [**oxidized/*****reduced***] (to water).

[**Anabolic/*****Catabolic***] reactions break down more complex molecules into simpler ones and in the process release energy. Reactions that release energy that can be used to do work are [**endergonic/*****exergonic***]. Therefore, aerobic respiration is a(n) [**anabolic/*****catabolic***] process and is [**endergonic/*****exergonic***].

[**Endergonic/*****Exergonic***] reactions are also said to be spontaneous reactions. Does this mean that if we don't keep glucose in tightly sealed containers it will spontaneously interact with atmospheric oxygen and turn into carbon dioxide and water? The answer is obviously no.

Spontaneous reactions rarely occur "spontaneously" because all chemical reactions, even those that release energy, require some addition of energy—the energy of activation—before they can occur. One way of supplying this energy is to add heat. An example is heating a marshmallow over a flame or campfire. When enough heat is added to reach (or overcome) the activation energy, the sugar in the marshmallow reacts by oxidizing. (Burning is a form of oxidation.) The marshmallow will continue to burn even if you remove it from the campfire. As the marshmallow burns, carbon dioxide and water are formed as products of the reaction, and the energy that was stored in the bonds of the sugar is released as heat.

If our cells used heat to overcome activation energies in metabolism, they would probably burn up like the marshmallow did. Instead, living systems use protein catalysts or enzymes to lower the energy of activation without adding heat. In addition, the metabolic breakdown of sugars is carried out in a controlled series of reactions. At each step or reaction in the sequence, a small amount of the total energy is released. Some of this energy is still lost as heat. The rest is converted to other forms that can be used in the cell to drive or fuel coupled endergonic reactions or to make ATP.

## Activity 9.2 Modeling cellular respiration: How can cells convert the energy in glucose to ATP?

Using your textbook, lecture notes, and the materials available in class (or those you devise at home), model both fermentation (an anaerobic process) and cellular respiration (an aerobic process) as they occur in a plant or animal cell. Each model should include a dynamic (working or active) representation of the events that occur in glycolysis.

### Building the Model

- Use chalk on a tabletop or a marker on a large sheet of paper to draw the cell membrane and the mitochondrial membranes.
- Use playdough or cutout pieces of paper to represent the molecules, ions, and membrane transporters or pumps.
- Use the pieces you assembled to model the processes of fermentation and aerobic respiration. Develop a dynamic (claymation-type) model that allows you to manipulate or move glucose and its breakdown products through the various steps of both fermentation and aerobic respiration.
- When you feel you have developed a good working model, demonstrate and explain it to another student.

Be sure your model of **fermentation** includes and explains the actions and roles of the following:

glycolysis
cytoplasm
electrons
protons
glucose
$NAD^+$
NADH

ADP
$\textcircled{P_i}$
ATP
pyruvate
ethyl alcohol (or lactic acid)
substrate-level phosphorylation

Be sure your model of **cellular respiration** includes and explains the actions and roles of the following:

glucose
oxygen
carbon dioxide
pyruvate
acetyl CoA
$NAD^+$
NADH
FAD
$FADH_2$
ADP
$P_i$
ATP
water

electron transport chain
mitochondria
inner mitochondrial membrane
outer mitochondrial membrane
$H^+$
electrons ($e^-$)
chemiosmosis
ATP synthase (proton pumps)
cristae
proton gradients
oxidative phosphorylation
substrate-level phosphorylation
oxidative phosphorylation

**Use your models to answer the questions.**

1. The summary formula for cellular respiration is

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{Energy}$$

| a. At what stage(s) in the overall process is each of the reactants used? | | b. At what stage(s) in the overall process is each of the products produced? | | |
|---|---|---|---|---|
| $C_6H_{12}O_6$ + | $6\ O_2$ → | $6\ CO_2$ + | $6\ H_2O$ + | Energy |
| Glycolysis | Oxidative phosphorylation | Pyruvate Acetyl CoA and Krebs cycle | Oxidative phosphorylation | ATP/glucose<br>Glycolysis (2),<br>Krebs (2 GTP),<br>oxidative phosphorylation (up to 34) |

2. In cellular respiration, the oxidation of glucose is carried out in a controlled series of reactions. At each step or reaction in the sequence, a small amount of the total energy is released. Some of this energy is lost as heat. The rest is converted to other forms that can be used by the cell to drive or fuel coupled endergonic reactions or to make ATP.

| a. What is/are the overall function(s) of glycolysis? | b. What is/are the overall function(s) of the Krebs cycle? | c. What is/are the overall function(s) of oxidative phosphorylation? |
|---|---|---|
| Oxidation of glucose to 2 pyruvate. Generates 2 ATP and 2 NADH per glucose | Oxidation of pyruvate/acetyl CoA to carbon dioxide. Generates 2 GTP, 6 NADH, and 2 $FADH_2$ per glucose. | Oxidation of NADH and $FADH_2$ to $H_2O$ (and NAD or FAD). Generates $H^+$ ion concentration gradient and therefore ATP. |

3.

| Are the compounds listed here *used* or *produced* in: | Glycolysis? | The Krebs cycle? | Oxidative phosphorylation? |
|---|---|---|---|
| Glucose | Used | | |
| $O_2$ | | | Used |
| $CO_2$ | | Produced | |
| $H_2O$ | | Produced (GTP) | Produced |
| ATP | Produced | | Produced |
| ADP + $\textcircled{P_i}$ | Produced and used | Used | Used |
| NADH | Produced | | Used |
| $NAD^+$ | Used | Used | |