Notes to Instructors

Chapter 7 Inside the Cell

What is the focus?

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 like 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, like 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.

Activity 7.1 What makes a cell a living organism?

What is this activity designed to do?

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?

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.

Most students 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 dark periods. 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 like 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 7.1 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?

1. Plasma or cell membrane
2. Nucleic acid (for example, DNA)
3. Ribosomes

b. What is the function of each structure or component listed in part a?

1. A selectively permeable cell membrane allows the cell to control what enters and exits the cell.
2. DNA contains the genetic information for producing all of the macromolecules required by the cell—for example, enzymes, carbohydrates, structural proteins, etc.
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?

1. Double-membrane-bound nucleus containing chromosomes complexed with histone proteins.
2. Double-membrane-bound mitochondria for use in aerobic cellular respiration.
3. Cytoskeleton.
4. Endoplasmic reticulum and Golgi apparatus.
5. Centrosome for microtubule and spindle production. In animal cells, the centrosome contains a pair of centrioles.
6. Peroxisomes for a variety of functions, including generating hydrogen peroxide from oxygen and degrading it to water.
7. Lysosomes for intracellular digestion of macromolecules.

b. A eukaryotic plant cell?

8. Double-membrane-bound nucleus containing chromosomes complexed with histone proteins.
9. Double-membrane-bound mitochondria for use in aerobic cellular respiration.
10. Cytoskeleton.
11. Endoplasmic reticulum and Golgi apparatus.
12. Microtubule organizing center (MTOC) for microtubule and spindle production. In general, plants do not have centrioles. Only a few cell types (e.g., in ferns and gymnosperms) develop centrioles.
13. Peroxisomes for a variety of functions, including generating hydrogen peroxide from oxygen and degrading it to water.
14. Double-membrane-bound chloroplasts for photosynthesis.
15. Central vacuole for storage and for breakdown of waste products.
16. Cell wall.
17. 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 measure ments of the cell be if drawn to the same scale (5 nm real length = 2 cm)?

a. The radius of a microtubule (Refer to Summary Table 7.3 in *Biological Science*, 4th 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) = 1.0×10^{-21} centimeters cubed (cm^3).	$4/3 \times (1\ cm)^3 = 4.2\ cm^3$
e. The volume of the nucleus	$4/3\ \pi\ (80\ m)^3 = 2.1 \times 10^6\ m^3$
f. The volume of the cell	$4/3\ \pi\ (200\ m)^3 = 3.4 = 10^7\ m^3$

g. The volume of the Empire State Building is $1.05 \times 10^6\ m^3$. 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 8 Cell–Cell Interactions

What is the focus?

Most students understand that external signals interact with receptors in cells and that the interaction leads to a response by the cell. However, many fewer have a good understanding of these processes:

- how a protein signal that cannot cross the cell membrane can cause a response,

- how very low concentrations of signal molecules can produce high levels of response, and

- exactly what a cell does to respond to a signal.

Activity 8.1 How are chemical signals translated into cellular responses?

What is this activity designed to do?

In this activity, students model and compare the functions of a G-protein receptor system and a tyrosine-kinase receptor system. In addition, they are asked to use their knowledge of enzyme function from Chapter 3 to understand how a signal transduction pathway can amplify the response to a single signal molecule.

What misconceptions or difficulties can this activity reveal?

Modeling the G-protein receptor system and the tyrosine-kinase receptor system does not reveal misconceptions; rather, it tends to fill in missing information. Most students at the introductory level have little understanding of these systems.

Questions 1 and 2: These questions ask students to look back at their two models and consider how they are similar and how they differ. Although engaging in this type of comparative process seems standard to those of us who have been working in the sciences for years, it is not something that introductory students do automatically. Posing these types of questions helps students learn not only to ask themselves the questions but also to organize and clarify their own understanding of the individual processes they model.

Question 3: Because these pathways are called signal transduction pathways, many students seem to get the idea (or misconception) that once each carrier or enzyme in a given pathway "transduces" or moves the signal on to the next carrier or enzyme, its job is done. This question focuses students' attention on Figure 8.14 on page 141 in *Biological Science*, 4th edition, to help them understand the process of signal amplification—in other words, to understand that once a single enzyme in the pathway is activated, it can catalyze more than one reaction, and the product of that reaction can catalyze more than one, and so on.

Answers

Activity 8.1 How are chemical signals translated into cellular responses?

Chapter 8 in *Biological Science*, 4th edition, describes at least four types of signal receptors. Three of these—G-protein-linked receptors, tyrosine-kinase receptors, and ion-channel receptors—are plasma membrane proteins. Protein receptors found in the cytoplasm or nucleus of the cell are the fourth type. Some signals (for example, a protein hormone) interact with signal receptors in the cell membrane to initiate the process of signal transduction. This often involves changes in a series of different relay molecules in a signal transduction pathway. Ultimately, the transduced signal initiates an intracellular response. Other types of signals (for example, steroid hormones) can diffuse through the cell membrane and interact with intracellular receptors. For example, testosterone interacts with its receptor in the cell's cytoplasm, enters the nucleus, and causes the transcription of specific genes.

To help you understand how signal transduction occurs in cells, develop dynamic (claymation-type) models of both a G-protein receptor system and a tyrosine-kinase receptor system. Use playdough or cut out pieces of paper to represent all the structural components and molecules listed here under each system.

G-protein receptor system	**Tyrosine-kinase receptor system**
signal protein	signal protein

G-protein-linked receptor	tyrosine-kinase receptor
plasma membrane	plasma membrane
inactive and active G protein	inactive and active relay proteins
GTP and GDP	ATP and ADP
inactive and active enzyme	signal transduction pathway
signal transduction pathway	

Use your models to show how signal reception by each of the systems can lead to the release of Ca^{+} from the endoplasmic reticulum. Demonstrate and explain your models to another student group or to your instructor.

Use your models and the information in Chapter 8 of your textbook to answer the questions on the next page.

1. How are these two systems similar? Consider both structural similarities and similarities in how the systems function.

   In both systems, the receptor proteins are bound in the cell's membrane. Binding of signal molecules to the receptors activates them. Activated receptor(s) interact with inactive relay protein(s) and activate them. The role of the activated relay protein(s) is to activate other protein(s) to produce the cellular response.

2. How are the two systems different? Consider both structural differences and differences in how the systems function.

   The G-protein-linked receptor protein is a single unit that becomes functional when activated by its signal molecule. Two tyrosine-kinase receptor proteins must be activated by signal molecules and aggregate to become activated.

   The activated G-protein-linked receptor protein activates the G protein, which is also membrane bound, by converting an associated GDP to GTP. The activated G protein then moves along the membrane and activates a specific membrane-bound enzyme, which produces the cellular response.

   The activated tyrosine-kinase receptor aggregate can activate up to 10 different specific relay proteins inside the cell and therefore produce multiple responses. The activated relay proteins are not membrane bound. Each type of activated relay molecule can activate a different transduction pathway and produce a different cellular response.

3. Both systems can generate elaborate multistep signal transduction pathways. These pathways can greatly amplify the cell's response to a signal; the more steps in the pathway, the greater the amplification of the signal. Explain how this amplification can occur. (Review Figure 8.14 on page 141 in your textbook.)

   In a signal transduction pathway, each activated enzyme or second messenger has the potential to catalyze more than one reaction. Each of its reaction products similarly has the potential to trigger more than one reaction. As a result, the effects produced by a single signal molecule can be greatly amplified.

Notes to Instructors

Chapter 9 Cellular Respiration and Fermentation

Chapter 10 Photosynthesis

What is the focus?

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.

Integrate Your Understanding

Activity 9.1 A Quick Review of Energy Transformations

What is this activity designed to do?

This activity adds consideration of the terms *oxidation* and *reduction* to the energy relationships students learned in Chapter 2.

What misconceptions or difficulties can this activity reveal?

This activity reviews the information presented in Chapter 2 and helps students integrate into that an understanding of oxidation and reduction reactions that occur in living organisms.

Activity 9.2 Modeling Cellular Respiration

What is this activity designed to do?

This activity 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.

What misconceptions or difficulties can this activity reveal?

By doing this modeling exercise, 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. Many students don't understand what the cell structures 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 in the process each product is made. Many students have difficulty answering most parts of this question.

Question 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. Instructors 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? These questions should help students understand this concept 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 topics 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. To answer this question, students must integrate an understanding of osmotic relationships from Chapter 6 with an understanding of the structure and function of ATP.

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).

Extend Your Understanding

Activity 9.3 Cell Respiration—Experimental scenarios

What is this activity designed to do?

In this activity, students work through problems and calculations that require them to use their understanding of cellular respiration and apply it to a novel situation.

What misconceptions or difficulties can this activity reveal?

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

Part c: 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 Modeling Photosynthesis

What is this activity designed to do?

This activity is 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 this activity reveal?

Students have the same difficulties in understanding photosynthesis that they have in 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.

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.

Extend Your Understanding

Activity 10.2 Chloroplast Function under Different Conditions

What is this activity designed to do?

This activity is 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.

Activity 10.3 How do C_3, C_4, and CAM photosynthesis compare?

What is this activity designed to do?

This activity is 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 this activity reveal?

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.

Answers

Integrate Your Understanding

Activity 9.1 A Quick Review of Energy Transformations

Review pages 27–30 of Chapter 2 and pages 157–161 of Chapter 9 in *Biological Science*, 4th edition. Then complete the following 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 cut out 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:

gcolysis
cytoplasm
electrons
protons
glucose
NAD^+
NADH
ADP
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
$FADH_2$
electron transport chain
mitochondria
inner mitochondrial membrane
outer mitochondrial membrane
H^+
electrons (e^-)
chemiosmosis
ATP synthase (proton pumps)
cristae

ADP	proton gradients
P_i	oxidative phosphorylation
ATP	substrate-level phosphorylation
Water	oxidative phosphorylation

Use your models and the information in Chapter 9 of *Biological Science,* 4th edition, to answer these questions.

1. The summary formula for cellular respiration is

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

a. -Where is each of the reactants the overall process?

b. Where is each of the products produced in used in the overall process?

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

Glycolysis	Oxidative phosphory- lation	Pyruvate→ Acetyl CoA and Krebs	Oxidative phosphory- lation	ATP/glucose→ Glycolysis (2), Krebs cycle(2 GTP),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 2pyruvate. Generates 2ATP and 2 NADH perglucose.	Oxidation ofpyruvate/acetyl CoA tocarbon dioxide. Generates 2 GTP, 6NADH, 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?	Oxidativephosphorylation?
Glucose	Used	O_2	Used
CO_2		Produced	
H_2O			Produced
ATP	Produced	Produced (GTP)	Produced

$ADP + P_i$	Produced & used	Used	Used
NADH	Produced	Produced	Used
NAD^+	Used	Used	Produced

4. The cell's supply of ADP, P_i, and NAD^+ is finite (limited). What happens to cellular respiration when all of the cell's NAD^+ has been converted to NADH?

   If NAD is unavailable, the cell is unable to conduct any processes that involve the conversion of NAD^+ to NADH. Because both glycolysis and the Krebs cycle produce NADH, both of these processes shut down when there is no available NAD^+.

5. If the Krebs cycle does not require oxygen, why does cellular respiration stop after glycolysis when no oxygen is present?

   When no oxygen is present, oxidative phosphorylation cannot occur. As a result, the NADH produced in glycolysis and the Krebs cycle cannot be oxidized to NAD^+. When no NAD^+ is available, pyruvate cannot be converted to the acetyl CoA that is required for the Krebs cycle.

6. Many organisms can withstand periods of oxygen debt (anaerobic conditions). Yeast undergoing oxygen debt converts pyruvic acid to ethanol and carbon dioxide. Animals undergoing oxygen debt convert pyruvic acid to lactic acid. Pyruvic acid is fairly nontoxic in even high concentrations. Both ethanol and lactic acid are toxic in even moderate concentrations. Explain why this conversion occurs in organisms.

   As noted in question 4, when no NAD^+ is available, even glycolysis stops. No ATP will be produced, and the cell (or organism) will die. The conversion of pyruvic acid (pyruvate) to lactic acid (or ethanol) requires the input of NADH and generates NAD^+. This process, called fermentation, allows the cell to continue getting at least 2 ATP per glucose.

7. How efficient is fermentation? How efficient is cellular respiration? Remember that efficiency is the amount of useful energy (as ATP) gained during the process divided by the total amount of energy available in glucose. Use 686 kcal as the total energy available in 1 mol of glucose and 8 kcal as the energy available in 1 mol of ATP.

Efficiency of fermentation

8 kcal/mole of ATP × 2 ATP = 16 kcal

$\frac{\text{16 kcal/2 moles of ATP}}{\text{686 kcal/mole of glucose}} = 2.3\%$

Efficiency of aerobic respiration

8 kcal/mole of ATP × 38 ATP(maximum) = 304 kcal

$\frac{\text{304 kcal/38 moles of ATP}}{\text{686 kcal/mole of glucose}} = 44.3\%$

8. a. Why can't cells store large quantities of ATP? (*Hint:* Consider both the chemical stability of the molecule and the cell's osmotic potential.)

   ATP is highly reactive at normal body temperatures and therefore difficult for cells to store for any period of time. (In the lab, ATP is usually stored at very low temperatures, for example, at –20°C.) In addition, ATP is a relatively small molecule. As a result, if cells could store high concentrations of ATP, their osmotic potential would change. This is also why cells don't store glucose. The cells would become hypertonic to the fluid around them and could pick up enough water to burst.

   b. Given that cells can't store ATP for long periods of time, how do they store energy?

      Instead of storing ATP, cells tend to store energy as fats, oils, or starches.

c. What are the advantages of storing energy in these alternate forms?

These are very large molecules and, as a result, do not have as great an effect on osmotic potential. They are also much more stable chemically than ATP is.

9. To make a 5 *M* solution of hydrochloric acid, we add 400 ml of 12.5 *M* hydrochloric acid to 600 ml of distilled water. Before adding the acid, however, we place the flask containing the distilled water into the sink because this solution can heat up so rapidly that the flask breaks. How is this reaction similar to what happens in chemiosmosis? How is it different?

Similarities	Differences
In both processes, as we add the acid tothe water, we are generating a difference in concentration between the two, or a H^+ ion gradient. As the H^+ ions flow down this gradient (that is, mix with the water), they release energy in the form of heat.	Chemiosmosis also sets up a H^+ ion concentration gradient; however, the energy release is controlled as the H^+ ions pass through the ATP synthase molecules and ATP is generated. Some energy is lost as heat, but much of it is captured in the chemical bonds of ATP.

Extend Your Understanding

Activity 9.3 Cell Respiration—Experimental scenarios

a. If it takes 1,000 g of glucose to grow 10 g of an anaerobic bacterium, how many grams of glucose would it take to grow 10 g of that same bacterium if it was respiring aerobically? Estimate your answer. For example, if it takes *X* amount of glucose to grow 10 g of anaerobic bacteria, what factor would you have to multiply or divide *X* by to grow 10 g of the same bacteria aerobically? Explain how you arrived at your answer.

Aerobic respiration can produce a maximum of 38 ATP per glucose molecule. Anaerobic respiration can produce 2 ATP per glucose molecule. As a result, aerobic respiration is about 19 times more efficient. Therefore, you would need 19 times less glucose if respiring aerobically: 1000 g of glucose divided by 19 equals approximately 50 g of glucose required if respiration is aerobic.

b. Mitochondria isolated from liver cells can be used to study the rate of electron transport in response to a variety of chemicals. The rate of electron transport is measured as the rate of disappearance of O_2 from the solution using an oxygen-sensitive electrode.

How can we justify using the disappearance of oxygen from the solution as a measure of electron transport?

Use the balanced equation for aerobic respiration:

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

If the final energy produced is 38 ATP, then for every 6 oxygen molecules consumed (or 6 moles of oxygen consumed), we expect 38 molecules of ATP (or moles of ATP) to be produced.

c. Humans oxidize glucose in the presence of oxygen. For each mole of glucose oxidized, about 686 kcal of energy is released. This is true whether the mole of glucose is oxidized in human cells or burned in the air. A calorie is the amount of energy required to raise the temperature of 1 g of water by 1°C; 686 kcal = 686,000 cal. The average human requires about 2000 kcal of energy per day, which is equivalent to about 3 mol of glucose per day. Given this, why don't humans spontaneously combust?

As noted in question 9, during cellular respiration, the energy from the oxidation of glucose is not released all at once (as it is in burning). Instead, each of the reactions in glycolysis, the Krebs cycle, and electron transport releases a small amount of the energy stored in the molecules. Much of this energy is captured as

NADH, $FADH_2$, ATP, or GTP. Some is lost as heat; however, the heat loss also occurs at each step and not all at once.

d. A gene has recently been identified that encodes for a protein that increases longevity in mice. To function in increasing longevity, this gene requires a high ratio of NAD^+/NADH. Researchers have used this as evidence in support of a "caloric restriction" hypothesis for longevity—that a decrease in total calorie intake increases longevity. How does the requirement for a high NAD^+/NADH ratio support the caloric restriction hypothesis?

   A decrease in calorie intake will decrease the rate of glycolysis and the Krebs cycle. Therefore, over a 24-hour period, there will be less NADH produced by glycolysis and the Krebs cycle, and the NAD^+/NADH ratio will increase.

e. An active college age athlete can burn more than 3000 kcal/day in exercise.

   If conversion of one mole of ATP to ADP + P_i releases about 7.3 kcal, roughly speaking, how many moles of ATP need to be produced per day in order for this energy need to be met?

   3000 kcal/day divided by 7.3 kcal/mole of ATP = 411 moles of ATP.

   If the molecular weight of ATP is 573, how much would the required ATP weigh in kilograms?

   411 moles of ATP times 573 grams per mole = 235,503 grams or 235 kilogram (about 518 pounds).

   Explain these results.

   ATP is broken down to ADP = P_i, which is continuously recycled to ATP during cell respiration.

Activity 10.1 Modeling Photosynthesis: How can cells use the sun's energy to convert carbon dioxide and water into glucose?

Activity 10.1 is designed to help you understand the following:

1. The roles photosystems I and II and the Calvin cycle play in photosynthesis
2. How and why C_4 and CAM photosynthesis differ from C_3 photosynthesis

Using your textbook, lecture notes, and the materials available in class (or those you devise at home), model photosynthesis as it occurs in a plant cell.

Your model should be a dynamic (working or active) representation of the events that occur in the various phases of C_3 photosynthesis.

Building the Model

- Use chalk on a tabletop, or a marker on a large sheet of paper, to draw the cell membrane and the chloroplast membranes.

- Use playdough or cut out pieces of paper to represent the molecules, ions, and membrane transporters or pumps.

- Use the pieces you assembled to model the processes involved in C_3 photosynthesis. Develop a dynamic (claymation-type) model that allows you to manipulate or move carbon dioxide and water and its breakdown products through the various steps of the process.

- When you feel you have developed a good working model, demonstrate and explain it to another student or to your instructor.

Your model of C_3 photosynthesis should include what occurs in photosystems I and II and in the Calvin cycle. For **photosystems I and II**, be sure your model includes and explains the roles of the following:

$NADP^+$	ATP	chemiosmosis
NADPH	water and oxygen	ATP synthase
ADP	H^+	e^- carriers in thylakoid
P_i	e^-	membranes

Also indicate where in the plant cell each item is required or produced.

For the **Calvin cycle**, be sure your model includes and explains the roles of the following:

glucose	NADPH
C_3 or three-carbon sugars	ATP
carbon dioxide	

Also indicate where in the plant cell each item is required or produced.

After you've modeled C_3 photosynthesis, indicate how the system would be altered for C_4 and CAM photosynthesis.

- Indicate where in the cells of the leaf PEP carboxylase exists and how it reacts to capture CO_2. Be sure to indicate the fate of the captured CO_2.

- Do the same for PEP carboxylase in CAM plants.

Use your model and the information in Chapter 10 of *Biological Science*, 4th edition, to answer these questions.

1. The various reactions in photosynthesis are spatially segregated from each other within the chloroplast. Draw a simplified diagram of a chloroplast and include these parts: outer membrane, grana, thylakoid, lumen, stroma/matrix.

Refer to Figure 10.16 on page 184 of your textbook.

a. Where in the chloroplast do the light reactions occur?	In the thylakoid membranes
b. Where in the chloroplast is the chemiosmotic	Across the thylakoid membrane; H^+ ionsare pumped

gradient developed?

into the thylakoid space.

c. Where in the chloroplast does the Calvin cycle occur?

In the stroma or liquid portion of the chloroplast

2. In photosynthesis, the reduction of carbon dioxide to form glucose is carried out in a controlled series of reactions. In general, each step or reaction in the sequence requires the input of energy. The Sun is the ultimate source of this energy.

a What is/are the overall function(s) of photosystem I?

In noncyclic photosphosphorylation, photosystem I produces NADPH. In cyclic photophosphorylation, photosystem I produces ATP.

b What is/are the overall function(s) of photosystem II?

Photosystem II generates ATP. To fill the electron hole in photosystem II, water is split into 2 H^+, 2e^-, and $^1/_2$ O_2. (The electron from photosystem II fills the electron hole in photosystem I.)

c What is/are the overall function(s) of the Calvin cycle?

The Calvin cycle uses the ATP and NADPH generated in the light reactions to reduce CO_2 to three-carbon compounds in a cyclic series of reactions that regenerates the original five-carbon sugar required to accept the CO_2. The three-carbon compounds can be used to make glucose or other organic compounds required by the cells.

3. Are the compounds listed here *used* or *produced* in:

	Photosystem I?	Photosystem II?	The Calvin cycle?
Glucose			Produced
O_2		Produced from the breakdown of H_2O	
CO_2			Used
H_2O		Used to produce 2 H^+, 2e^-, and $^1/_2$ O_2	
ATP	Produced (in cyclic photophosphory-lation)	Produced	Used
ADP + P_i	Used	Used	Produced
NADPH	Produced		Used
$NADP^+$	Used		Produced

4. Which light reaction system (cyclic or noncyclic) would a chloroplast use in each situation?

a. Plenty of light is available, but the cell contains little $NADP^+$.

If there is little $NADP^+$, there must be much NADPH. This

b. There is plenty of light, and the cell contains a high concentration of $NADP^+$.

In this case, it appears that NADPH is being

could occur if the Calvin cycle is not using up the NADPH. For example, if CO_2 levels are low, little NADPH will be used to make glucose. Under these circumstances, the system would switch to cyclic photophosphorylation and gain ATP, which can be used both in photosynthesis and in other types of metabolism.

used rapidly (therefore the high levels of $NADP^+$). As a result, the system would switch to noncyclic photophosphorylation, which produces both ATP and NADPH.

5. All living organisms require a constant supply of ATP to maintain life. If no light is available, how can a plant make ATP?

   Keep in mind that it is not always light and that not all cells of a plant are directly exposed to light. For example, cells on the interior of a plant stem and those in the roots have little, if any, exposure to light. Plants, like other eukaryotic organisms on Earth, also contain mitochondria. Plant cells undergo glycolysis in the cytoplasm and transfer acetyl CoA to mitochondria, where it enters the Krebs cycle. The NADH and $FADH_2$ produced during the Krebs cycle then undergo oxidative phosphorylation to produce ATP.

Extend Your Understanding

Activity 10.2 Chloroplast Function under Different Conditions

Chloroplast thylakoids can be isolated and purified for biochemical experiments. Shown below is an experiment in which pH was measured in a suspension of isolated thylakoids before and after light illumination (first arrow). At the time indicated by the second arrow, a chemical compound was added to the thylakoids. Examine these data and address the following questions.

a. Based on your understanding of the function of the chloroplasts, why does turning on the light cause the pH in the solution outside the thylakoids to increase?

   Electron transfer (photosystems II and I) in the thylakoid membrane resulted in pumping of H^+ from stroma (outside) to inside thylakoid. As a result, the H^+ concentration outside the thylakoids became lower and the pH increased.

b. Given the response, the chemical added was probably an inhibitor of:

   (A) oxidative phosphorylation

   (B) ATP synthase

   (C) NADPH breakdown

   (D) electron transport chain between photosystems I and II

   (E) rubisco

   Justify your answer.

   Disrupting the electron transport chain between photosystems II and I would prevent transport of H^+ ions into the thylakoid space.

Activity 10.3 How do C_3, C_4, and CAM photosynthesis compare?

1. Carbon dioxide enters plant leaves through the stomata, while oxygen (the photosynthetic waste product) and water from the leaves exit through the stomata. Plants must constantly balance both water loss and energy gain (as photosynthesis). This has led to the evolution of various modifications of C_3 photosynthesis.

	C_3	C_4	CAM
Draw simplified diagrams of the cross sections of a leaf from a C_3, a C_4 and a CAM plant.	See Figure 10.20.	See Figure 10.22.	CAM leaf anatomy is similar to C_3 leaf anatomy.
a. How are the leaves similar?	All have stomata, epidermal cells that lack chloroplasts, mesophyll cells with chloroplasts, and veins that conduct water and the products of photosynthesis.		
b. How are the leaves different?	C_4 plants have large bundle-sheath cells not found in the others. In C_4 plants, the Calvin cycle occurs only in the bundle-sheath cells.		
c. How and when does carbon dioxide get into each leaf?	During daylight hours, when stomata are open	During cooler parts of the day, when stomata are open	At night, when it is cool and stomata are open
d. Which enzyme(s) (1) capture carbon dioxide and (2) carry it to the Calvin cycle?	The CO_2 is picked up by the enzyme, rubisco, which catalyzes the first step in the Calvin cycle.	PEP carboxylase in the mesophyll cells converts CO_2 to a four-carbon organic acid, which is transported to the bundle-sheath cells, where it is converted to CO_2 and PEP, and rubisco catalyzes the first step in the Calvin cycle.	PEP carboxylase in the mesophyll cells converts CO_2 to a four-carbon organic acid, which is trans-ported to the cells' central vacuoles and can later be converted back to CO_2 and PEP. The CO_2 can then be picked up by rubisco and used in the Calvin cycle in mesophyll cells.

e What makes C_4 photosynthesis more efficient than C_3 photosynthesis in tropical climates?

PEP carboxylase is much more efficient than rubisco at picking up CO_2. As a result, C_4 plants can capture large quantities of CO_2 and store it as a four-carbon organic compound in a relatively short period of time. This means that during the hottest parts of the day, the stomata can close to reduce water loss. Even with the stomata closed, however, the Calvin cycle can continue by using the stored CO_2. This system also maintains a relatively high ratio of CO_2 to O_2 in the cells that rely on rubisco, the bundle-sheath cells. This greatly reduces the amount of photorespiration in these plants.

f How is CAM photosynthesis advantageous in desert climates?

Stomata can be open at night when there is less evaporative loss of water and closed during the day. At night, PEP carboxylase allows desert plants to store CO_2 as a four-carbon organic acid. However, the amount that can be stored in the central vacuole of its photosynthetic cells is finite. This stored CO_2 can then be used during the day to support the Calvin cycle.

2. Photosynthesis evolved very early in Earth's history. Central to the evolution of photosynthesis was the evolution of the enzyme rubisco (an abbreviation for ribulose bisphosphate carboxylase oxidase). To the best of our knowledge, all photosynthetic plants use rubisco. Rubisco's function is to supply carbon dioxide to the Calvin cycle; however, it does this only if the ratio of carbon dioxide to oxygen is relatively high. (For comparison, a relatively high ratio of carbon dioxide to oxygen is 0.03% carbon dioxide to 20% oxygen.)

When the ratio of carbon dioxide to oxygen becomes low, the role of rubisco switches and it catalyzes photorespiration, the breakdown of glucose to carbon dioxide and water.

a. Why could we call photorespiration a "mistake" in the functioning of the cell?

   Photorespiration could be called a "mistake" because under high O_2/CO_2 conditions, rubisco breaks down glucose into carbon dioxide and water. No useful energy is gained from this process, however.

b. Rubisco is thought to have evolved when Earth had a reducing atmosphere. How does this help explain this "mistake"?

   When the first photosynthetic organisms arose, the early Earth's atmosphere contained little, if any, oxygen. Rubisco would have functioned very well under these conditions. It was only later, when the concentration of oxygen in the atmosphere increased considerably, that rubisco's ability to oxidize glucose became evident.

Notes to Instructors

Chapter 11 The Cell Cycle

What is the focus?

Most students can recite what happens in each phase of mitosis. However, many have difficulty translating those descriptions into visual pictures of a cell with a particular number of chromosomes.

Activity 11.1 What is mitosis?

What is this activity designed to do?

The activity is designed to give students practice in translating their knowledge of what goes on in the various phases of mitosis into visual representations.

What misconceptions or difficulties can this activity reveal?

Most students don't have difficulty reciting what events occur in each stage of mitosis or meiosis. If you ask them to draw what is occurring in each of these stages and give a specific chromosome complement (as in question 3 in Activity 11.1), however, many have a difficult time. Here are two common reasons for the difficulty:

- The students do not understand how many chromosomes the cell contains. For example, if a question indicates that a eukaryotic cell has a full complement of eight chromosomes, many students may not understand this means that the cell has eight total chromosomes, or four pairs of chromosomes.

- The students have memorized the list of events that occur in each stage, but they have not translated this into a real understanding of the events.

In either case, asking students to draw cells in different stages of cell division will give them a better understanding of the overall process.

Question 2: Some students don't understand that mitosis and meiosis occur only in eukaryotes. This question is meant to point out that mitosis does not occur in prokaryotes, for example, bacteria.

Question 6: Students are often confused about how to count the number of chromosomes in a cell. A general rule or convention is that chromosomes should be counted by the number of centromere regions present. Using this convention, we count two chromatids attached to a common centromere region as one chromosome. When sister chromatids separate to opposite poles, each daughter chromosome has its own centromere region and is now counted separately. To help avoid confusion, this question asks about both the number of centromeres visible and the number of chromatids attached to centromeres to determine student understanding.

Answers

Activity 11.1 What is mitosis?

What is the role of mitosis?

1. What is the overall purpose of mitosis?

   The purpose of mitosis is to produce daughter cells that are identical to the parent cell. To do this, the cells must first duplicate all of their chromosomes. Then the chromosomes must be equally divided among the daughter cells such that each has the same complement (number and kinds) of chromosomes as in the parent cell.

2. In what types of organism(s) does mitosis occur? What type of cell division occurs in bacteria?

   Mitosis occurs in all eukaryotic organisms. Bacteria undergo a type of cell division called fission. Fission involves duplication of the DNA, or genophore, and subdivision of the cell into two daughters, each of which contains a copy of the DNA from the parent.

What are the stages of mitosis?

3. The fruit fly, *Drosophila melanogaster*, has a total of eight chromosomes (four pairs) in each of its somatic cells. Somatic cells are all cells of the body except those that will divide to form the gametes (ova or sperm). Review the events that occur in the various stages of mitosis.

   Keep in mind that the stages of cell division were first recognized from an examination of fixed slides of tissues undergoing division. On fixed slides, cells are captured or frozen at particular points in the division cycle. Using these static slides, early microscopists identified specific arrangements or patterns of chromosomes that occurred at various stages of the cycle and gave these stages names (interphase, prophase, and so on). Later work using time-lapse photography made it clear that mitosis is a continuous process. Once division begins, the chromosomes move fluidly from one phase to the next.

Assume you are a microscopist viewing fruit-fly cells that are undergoing mitosis. In each of the circles (cell membranes) on the following page, draw what you would expect to see if you were looking at a cell in the stage of mitosis indicated. If no circle is present, draw what you would expect to see at the given stage.

See Figure 11.5 on pages 198–199 of your textbook for diagrams of the process of mitosis.

What are the products of mitosis?

4. How many cells are produced at the end of a single mitotic division?

   Two cells are produced at the end of a single mitotic division.

5. How many different kinds of cells are produced at the end of a single mitotic division?

   Only one kind of cell is produced. Two daughter cells are produced, but they are identical to each other and

to the parent cell that gave rise to them.

6. Six centromeres are observed in a prophase cell from another species of insect.

a. How many pairs of chromosomes does this organism contain? Three pairs

b. For each stage of mitosis, indicate the number of centromeres you would expect to find and the number of copies of chromosomes attached to each centromere.

Stage of mitosis:	Number of centromeres visible per cell	Number of chromosome copies attached to each centromere
Prophase	6	2
Anaphase	12	1

What controls mitosis?

7. Checkpoints in the normal cell cycle prevent cells from going through division if problems occur—for example, if the DNA is damaged.

   a. What forms do the checkpoints take? That is, how do they control whether or not cell division occurs?

      Several different cyclins are produced during interphase. Three of the major checkpoints in mitosis, the G_1, G_2, and M-phase checkpoints, appear to be controlled by cyclin-dependent kinases (Cdks). The ratio of Cdks to their cyclins determines their activity. The activities of the different activated Cdks control the cell cycle. The cell can move past a given stage of the cycle only when the appropriate checkpoint's Cdk has been activated.

   b. On this page, develop a handout or diagram to explain how these checkpoints work under normal conditions. Your handout should include a description of each checkpoint, where it acts in the cell cycle, and what each checkpoint does to control cell division.

      Refer to Figures 11.11 and 11.12, pages 204–205, which shows the molecular mechanisms associated with activity of the cyclin–Cdk complex called MPF. Here is an easy way to represent the G_1 and G_2 control points and their actions:

      Using a diameter of about 3 inches, draw the central set of arrows (Figure 11.12) on a piece of paper.

      On another piece of paper, draw a circle about 4 inches in diameter; around this circle, draw another circle about 6 inches in diameter. Draw the lines that show the activity of cyclins versus Cdk (Figure 11.11) between these two circles.

      Cut out the center of this circle.

      Place the circle over the cell-cycle arrow diagram you drew first to create the same diagram you see in Figure 11.12.

      Next, substitute the words "G_1 checkpoint" for MPF on the drawing. Now rotate the top sheet of paper so that the G_1 checkpoint lines up with its position in G_1 on the arrow diagram.

      Do the same for the G_2 checkpoint.

   c. Cancer results from uncontrolled cell division. Explain how mutations in one or more of the checkpoints might lead to cancer.

The basic function of each checkpoint is to determine whether the cell is functioning normally and should enter into or continue through division. If these checkpoints break down, they could allow any cell to continue through the cell cycle—that is, to divide. Cancer is uncontrolled cell division, so cancer can result from a breakdown of the operation of these checkpoints.