How Cells Harvest Chemical Energy 6

You need to eat and breathe because your cells need food and oxygen for energy. In every cell in your body, organic molecules and oxygen interact in a complex process called cellular respiration. In this process, food molecules such as glucose are broken down and the energy contained in their chemical bonds is used to make ATP. The ATP made in cellular respiration is then used to drive cellular activities. Right now, ATP produced in cellular respiration is being used to generate the nerve impulses from your eyes to your brain, to move your muscles, and to drive your heartbeat. This chapter explains how your cells harvest the energy that keeps you alive.

Organizing Your Knowledge

Exercise 1 (Introduction - Module 6.3)

Review the basic terms and concepts of cellular respiration by filling in the blanks below.

Right now, you are breathing at a steady rate of 12 to 20 breaths per minute. Breathing, or [1]_____, is necessary for life, but why? Breathing allows the body to take in [2]_____ gas and expel waste [3]_____. Your breathing is closely related to [4]_____, the aerobic harvest of the energy in food molecules by cells. Most of the time, most cells acquire energy by taking in both [5]_____ and [6]_____ from the blood. These two substances interact, the sugar is broken apart, and [7]_____ and [8]_____ are produced. In the process, some of the energy is stored in molecules of [9]_____, which provide the energy for body activities. To make enough ATP for their needs, average human beings must take in food that provides about [10]_____ kilocalories (kcal) of energy per day.

When using oxygen, cells are said to function [11]_____. Cells making ATP this way capture about [12]_____ of the energy in glucose. For short bursts, cells can make ATP [13]_____ — that is, without using oxygen. This process is much less efficient; it only banks about [14]_____ % of the energy in glucose. But it is useful during intense bursts of activity, such as sprinting or heavy lifting.

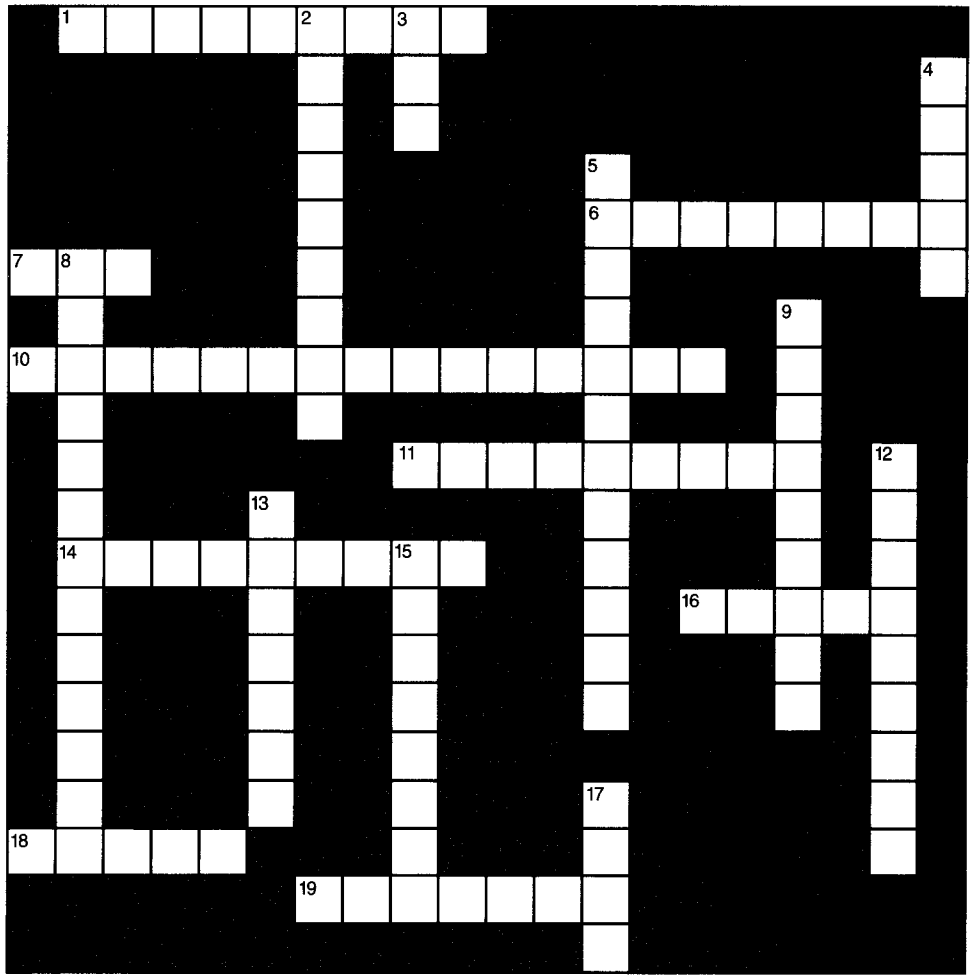
Muscles contain a mixture of two kinds of cells, or fibers, specialized either for aerobic or anaerobic ATP production. [15]_____ fibers can sustain repeated, long contractions, by continuously producing ATP via [16]_____cellular respiration. Slow fibers are long and [17]_____, maximizing their surface area and contact with nearby [18]_____ that deliver oxygen. They have many [19]_____, the structures where aerobic ATP breakdown occurs. And they are rich in [20]_____, a red protein related to hemoglobin that supplies O_2

molecules. The [21]_____ meat of a turkey leg consists mostly of myoglobin-rich slow muscle fibers. The white meat of a turkey breast, on the other hand, consists mostly of [22]_____ muscle fibers, which are specialized for quick, powerful bursts of flight. These fibers are [23]_____ and are more powerful than slow fibers, having [24]_____ mitochondria and [25]_____myoglobin than slow fibers. During intense activity, when the blood cannot deliver O_2 fast enough for aerobic cellular respiration, fast fibers can function anaerobically, making small amounts of ATP without oxygen. They don't completely break down [26]_____, and therefore do not capture all its energy, and instead of producing CO_2 they make [27]_____, which makes muscles [28]_____ and fatigue. This is why [29]_____ fibers are best at producing short bursts of power.

Human muscles contain both kinds of fibers. Their proportions vary from muscle to muscle, and person to person. A runner whose leg muscles are primarily composed of [30]_____ fibers would be more likely to excel in distance events, while an individual with an abundance of [31]_____ fibers might make a better sprinter.

Exercise 2 (Modules 6.4 – 6.7)

How does the cell capture the energy of organic molecules in ATP? Review the basic concepts by completing this crossword puzzle.



Across

1. The cell transfers energy by shuttling ____ from molecule to molecule.
6. Energy released in the electron transport chain moves ____ ions (H^+) across a membrane.
7. ATP is made from ____ and inorganic phosphate.
10. Substrate-level ____ is a simpler way to make ATP than chemiosmotic phosphorylation.
11. A sequence of electron carriers forms the electron ____ chain.
14. ____ is loss of an electron.
16. A molecule such as glucose is oxidized when it ____ an electron.
18. ____ is short for "oxidation-reduction."
19. Oxygen is ____ in cellular respiration.

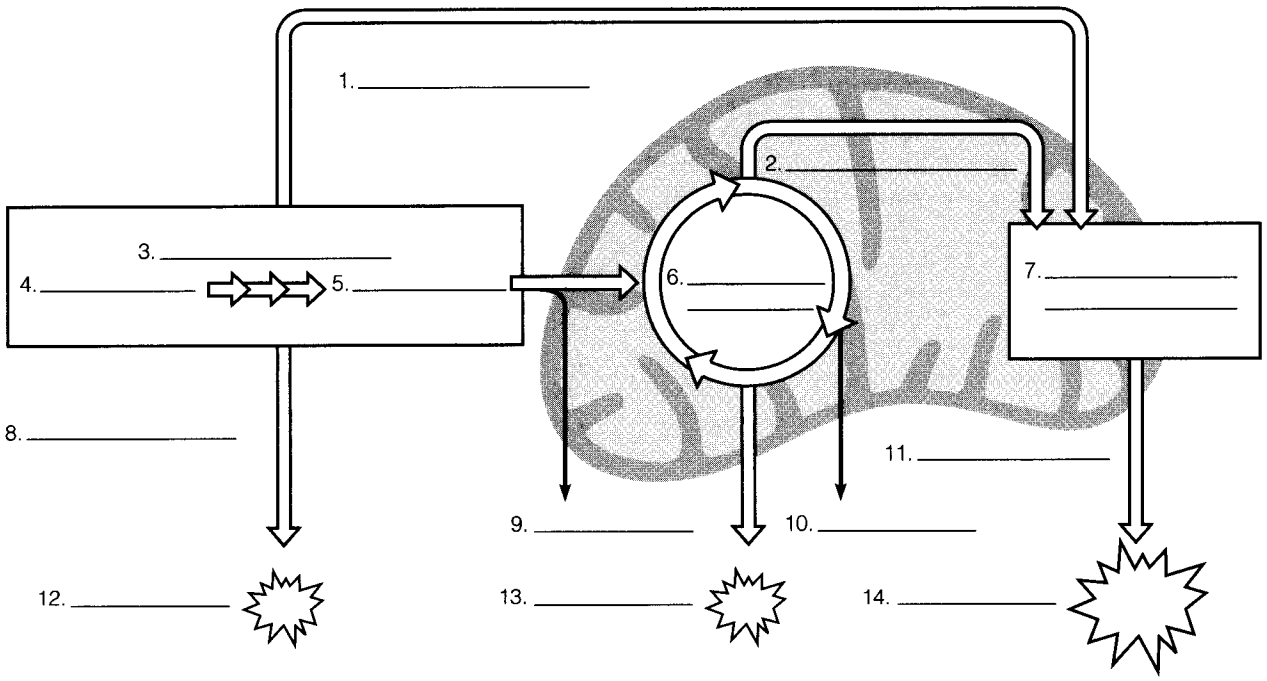
Down

2. ____ is gain of an electron.
3. A coenzyme called ____ is used to carry hydrogen atoms in redox reactions.
4. A molecule is reduced when it ____ an electron.
5. Most cells make most of their ATP via a process called ____.
8. A ____ enzyme strips hydrogen atoms from organic molecules.
9. ATP ____ use energy from a gradient of ion concentration to make ATP.
12. In substrate-level phosphorylation an enzyme transfers a ____ group to ATP.
13. NADH delivers electrons to an electron ____.
15. Glucose is ____ in cellular respiration.
17. NAD^+ picks up electrons and hydrogen, forming ____.

Exercise 3 (Module 6.8)

Web/CD Activity 6A *Overview of Cellular Respiration*

The illustration in Module 6.8 introduces the three stages of cellular respiration. After studying it, see if you can label the diagram below without referring to the text. Include **electron transport chain and chemiosmosis, pyruvic acid, mitochondrion, CO_2, high-energy electrons carried by NADH, Krebs cycle, glycolysis, cytoplasmic fluid, ATP, glucose,** and **NADH and $FADH_2$.** (Note: 3, 6, and 7 are processes, 8 and 11 are places, and the rest are inputs and outputs.)



Exercise 4 (Module 6.9)

Web/CD Activity 6B *Glycolysis*

Glycolysis is the first of three steps in cellular respiration. Review glycolysis by matching each phrase on the right with a term on the left. Some terms are used twice.

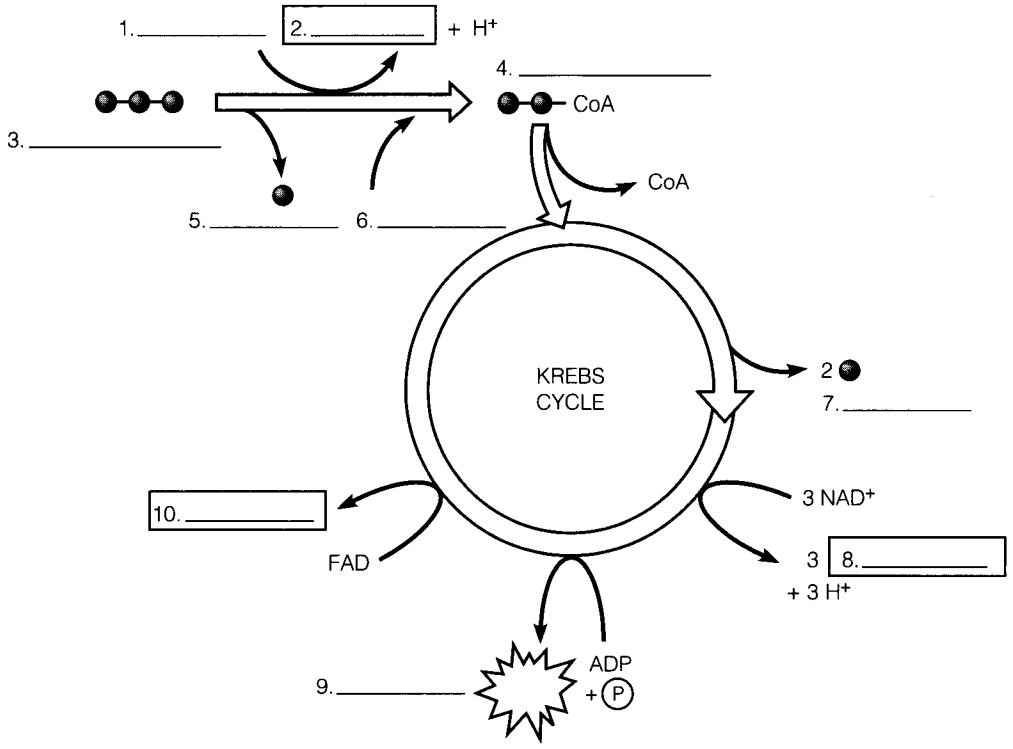
A. NADH
B. Pyruvic acid
C. ATP
D. NAD^+
E. Glucose
F. Glycolysis
G. ADP and P
H. Oxygen
I. Intermediate

_____ 1. Compound formed between glucose and pyruvic acid
_____ 2. Not involved in glycolysis
_____ 3. Fuel molecule broken down in glycolysis
_____ 4. Produced by substrate-level phosphorylation
_____ 5. Invested to energize glucose molecule at start of process
_____ 6. Reduced as glucose is oxidized
_____ 7. Glucose converted to two molecules of this
_____ 8. Assembled to make ATP
_____ 9. "Splitting of sugar"
_____ 10. Carries hydrogen and electrons from oxidation of glucose

Exercise 5 (Modules 6.10 – 6.11)

Web/CD Activity 6C *The Krebs Cycle*

Pyruvic acid from glycolysis is chemically altered and then enters the Krebs cycle, a series of steps that completes the oxidation of glucose. The energy of pyruvic acid is stored in NADH and $FADH_2$. To review these processes, fill in the blanks in the diagram below. (Try to do as many as you can without referring to the text.) Include the following: **NAD^+, pyruvic acid, CO_2, $FADH_2$, NADH, coenzyme A, ATP,** and **acetyl CoA.**



Exercise 6 (Module 6.12)

Web/CD Activity 6D *Electron Transport and Chemiosmosis*

Circle the correct words or phrases in parentheses to complete each sentence.

The [1] *(final, second)* stage of cellular respiration is the electron transport chain and synthesis of [2] *(glucose, ATP)* by [3] *(chemiosmosis, active transport).* The electron transport chain is a sequence of [4] *(electron, proton)* carriers built into the [5] *(outer, inner)* membrane of the mitochondrion. Molecules of [6] *(ADP, NADH)* bring hydrogens and electrons to the chain from glycolysis and [7] *(the Krebs cycle, chemiosmosis).* The electrons move along the chain from carrier to carrier in a series of redox reactions, finally joining with [8] *(H_2O, CO_2, O_2)* and H^+ from the surrounding solution to form [9] *(H_2O, CO_2, O_2).* Energy released by the electrons is used to move protons—[10] *(H^+ ions, ADP molecules)*—by [11] *(active transport, passive transport)* into the space between the inner and outer mitochondrial membranes.

The buildup of protons in the intermembrane space—a proton gradient—constitutes [12] *(kinetic, potential)* energy that the cell can tap to make [13] *(ATP, glucose).* The concentration of protons tends to drive them back through the membrane into the [14] *(inner*

compartment of the mitochondrion, cytoplasm of the cell), but protons can cross the membrane only by passing through special protein complexes, called [15] *(coenzyme As, ATP synthases).* As these complexes allow protons back through the membrane, their enzymes harness the energy of the moving protons to phosphorylate [16] *(NAD, ADP)* and make [17] *(NADH, ATP).* Thus, electron transport and chemiosmosis transform [18] *(most, some, a small portion)* of the energy extracted from glucose into the phosphate bonds of ATP.

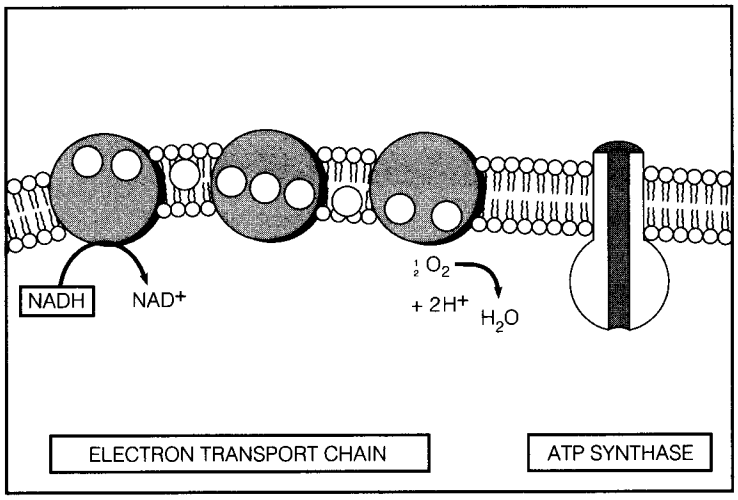
Exercise 7 (Modules 6.12 - 6.13)

Web/CD Activity 6D *Electron Transport and Chemiosmosis*

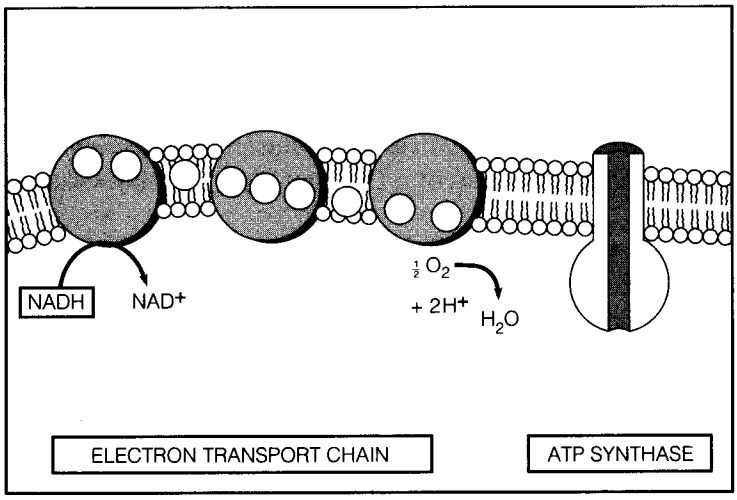
These diagrams will help you review electron transport, chemiosmosis, and how poisons disrupt them. In the first diagram, show how the processes work normally. Trace movement of an electron with an orange arrow, movement of H^+ ions (active transport and chemiosmosis) with black arrows, and formation of ATP with a pink arrow.

In the second diagram, draw arrows showing the movement of electrons and H^+ and the formation of ATP, as in the first diagram. Then draw a red line where each poison acts, to show how each of the poisons short-circuits the normal processes. Label the poisons **rotenone, cyanide, carbon monoxide, DNP,** and **oligomycin.**

1. Normal electron transport and chemiosmosis:



2. Effects of poisons:



Exercise 8 (Modules 6.8 – 6.14)

Web/CD Activity 6A *Overview of Cellular Respiration*
Web/CD Activity 6B *Glycolysis*
Web/CD Activity 6C *The Krebs Cycle*
Web/CD Activity 6D *Electron Transport and Chemiosmosis*

Check your overall understanding of cellular respiration by matching each of the phrases below with one of the three stages of the process. Use G for glycolysis, K for Krebs cycle, and E for electron transport and chemiosmosis.

_____ 1. Generates most of the ATP formed by cellular respiration
_____ 2. Begins the oxidation of glucose
_____ 3. Occurs outside the mitochondrion
_____ 4. Produces 4 ATPs per glucose by substrate-level phosphorylation, but 2 ATPs per glucose are used to get it started
_____ 5. Oxidizes NADH and $FADH_2$, producing NAD^+ and FAD
_____ 6. Carried out by enzymes in the matrix (fluid) of the mitochondrion
_____ 7. Here electrons and hydrogen combine with O_2 to form H_2O
_____ 8. Occurs along the inner mitochondrial membrane
_____ 9. Generates most of the CO_2 produced by cellular respiration
_____10. $FADH_2$ and NADH deliver hydrogen ions and electrons to this stage
_____11. ATP synthase makes ATP
_____12. Reduces NAD^+ and FAD, producing NADH and $FADH_2$

Exercise 9 (Module 6.15)

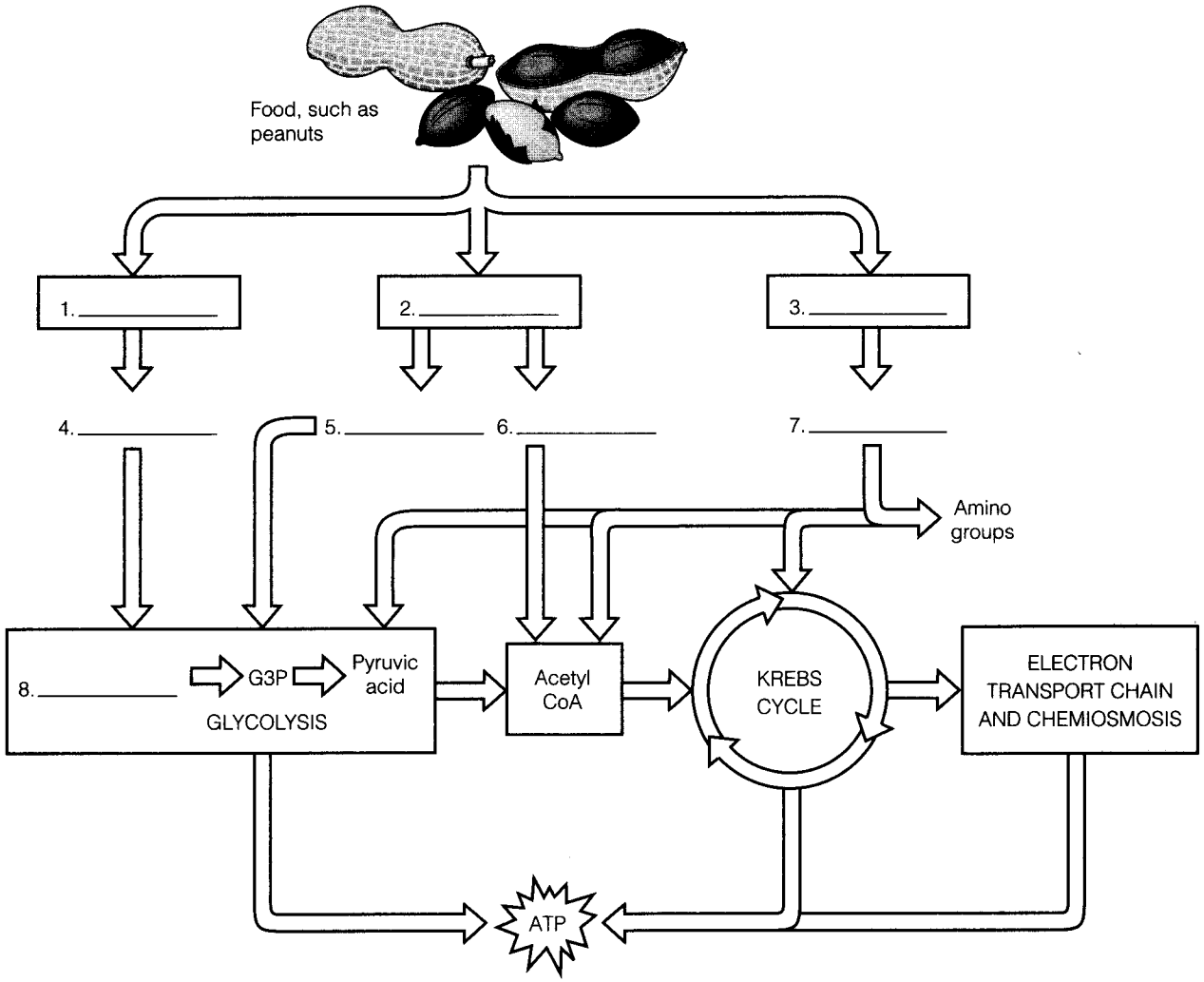
Web/CD Activity 6E *Fermentation*

Review fermentation by filling in the blanks below.

1. _____ anaerobes can make their ATP by fermentation or aerobic respiration.
2. _____ is an organism that normally uses aerobic respiration to produce ATP, but it can generate ATP without oxygen, via alcoholic fermentation.
3. Fermenters replenish their supply of NAD^+ by using NADH to oxidize _____ acid.
4. When oxygen is scarce, human _____ cells can make ATP by lactic acid fermentation.
5. Fermentation enables cells to make ATP in the absence of _____ .
6. For every molecule of glucose consumed, glycolysis produces two molecules of pyruvic acid, two molecules of ATP, and two molecules of _____ .
7. The waste products of alcoholic fermentation are _____ and carbon dioxide.
8. _____ acid fermentation is used to make cheese and yogurt.
9. Fermentation generates two _____ molecules for every molecule of glucose consumed.
10. A cell can use _____ to generate a small amount of ATP, but it must somehow recycle its supply of NAD^+.
11. Like aerobic respiration, alcoholic fermentation produces _____ gas as a waste product.
12. Strict _____ require anaerobic conditions and are poisoned by oxygen.

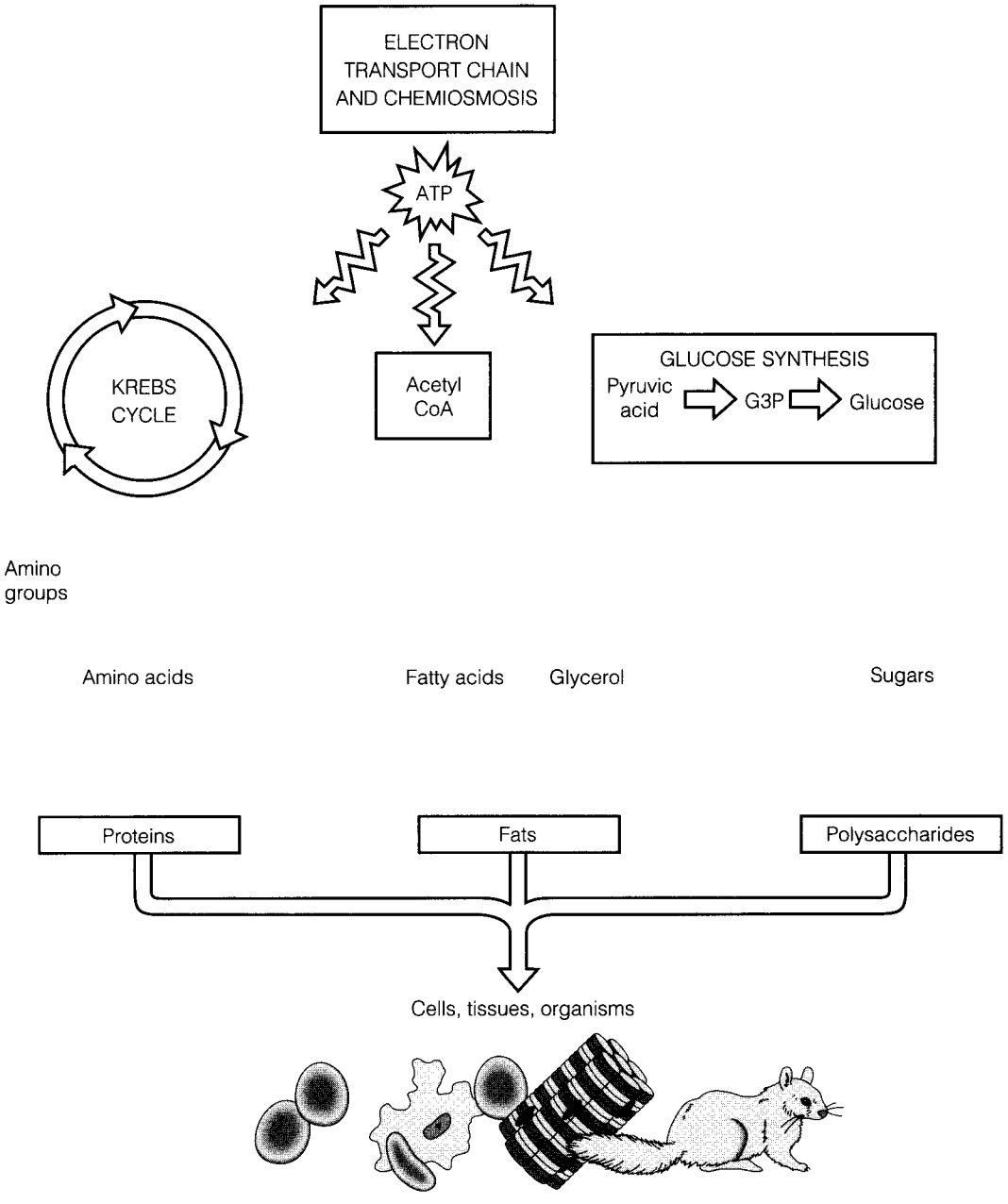
Exercise 10 (Module 6.16)

Review the molecules that can be used as fuel for cellular respiration by writing their names in the blanks in this diagram. Include **glucose, amino acids, fats, fatty acids, proteins, sugars, polysaccharides,** and **glycerol.**



Exercise 11 (Module 6.17)

Show how a cell obtains organic molecules for biosynthesis of proteins, polysaccharides, and fats by drawing the missing arrows on this diagram.



Testing Your Knowledge

Multiple Choice

1. A molecule is oxidized when it
   a. changes shape.
   b. gains a hydrogen (H^+) ion.
   c. loses a hydrogen (H^+) ion.
   d. gains an electron.
   e. loses an electron.

2. The main function of cellular respiration is
   a. breaking down toxic molecules.
   b. making ATP that powers cell activities.
   c. making food.
   d. producing chemical "building blocks" for cell structures.
   e. breaking down ATP, so that ADP and P can be reused.

3. In cellular respiration, _____ is oxidized and _____ is reduced.
   a. O_2 . . . ATP
   b. ATP . . . O_2
   c. glucose . . . O_2
   d. CO_2 . . . H_2O
   e. glucose . . . ATP

4. Most of the ATP produced in cellular respiration comes from
   a. glycolysis.
   b. chemiosmosis.
   c. lactic acid fermentation.
   d. biosynthesis.
   e. the Krebs cycle.

5. _____ is used and _____ is produced in the overall process of cellular respiration.
   a. CO_2 . . . H_2O
   b. O_2 . . . glucose
   c. H_2O . . . ATP
   d. glucose . . . CO_2
   e. ATP . . . O_2

6. The energy given up by electrons as they move through the electron transport chain is used to
   a. break down glucose.
   b. make NADH and $FADH_2$.
   c. pump H^+ through a membrane.
   d. oxidize water.
   e. manufacture glucose.

7. Fermentation is essentially glycolysis plus an extra step in which pyruvic acid is reduced to form lactic acid or alcohol and CO_2. This last step
   a. removes poisonous oxygen from the environment.
   b. extracts a bit more energy from glucose.
   c. enables the cell to recycle NAD^+.
   d. inactivates toxic pyruvic acid.
   e. enables the cell to make pyruvic acid into substances it can use.

8. A small amount of ATP is made in glycolysis and the Krebs cycle
   a. by transfer of a phosphate group from a fragment of glucose to ADP.
   b. using energy from the sun to perform the process of photosynthesis.
   c. by transport of electrons through a series of carriers.
   d. when electrons and hydrogen atoms are transferred to NAD^+.
   e. as a product of chemiosmosis.

9. The ATP synthase in a human cell gets energy for making ATP directly from
   a. sunlight.
   b. flow of H^+ through a membrane.
   c. oxidation of glucose.
   d. movement of electrons through a series of carriers.
   e. reduction of oxygen.

10. Which of the following describes glycolysis?
    a. It begins the oxidation of glucose.
    b. It produces a small amount of ATP.
    c. It generates NADH.
    d. It splits glucose to form two molecules of pyruvic acid.
    e. All of the above.

11. Most of the NADH that delivers high-energy electrons to the electron transport chain comes from
    a. chemiosmosis.
    b. the cytoplasm.
    c. glycolysis.
    d. biosynthesis.
    e. the Krebs cycle.

12. When protein molecules are used as fuel for cellular respiration, _____ are produced as waste.
    a. amino groups
    b. fatty acids
    c. sugar molecules
    d. molecules of lactic acid
    e. ethanol and CO_2

Essay

1. Describe the relationship between breathing and cellular respiration.
2. Compare the advantages and disadvantages of aerobic cellular respiration with the advantages and disadvantages of fermentation as methods of making ATP for cellular activities.
3. Compare the two mechanisms that generate ATP in cellular respiration—chemiosmotic phosphorylation and substrate-level phosphorylation. In what stage(s) of cellular respiration does each occur? Where does each get the energy for making ATP? Which produces the most ATP under aerobic conditions? Under anaerobic conditions?
4. Describe three ways in which poisons can interfere with cellular respiration.
5. Explain the roles of glycolysis and the Krebs cycle in the biosynthesis of organic molecules.

Applying Your Knowledge

Multiple Choice

1. Which of the following illustrates oxidation?
    a. $CO_2 + H_2O \longrightarrow C_6H_{12}O_6$
    b. $C_6H_{12}O_6 \longrightarrow CO_2 + H_2O$
    c. $ADP + P \longrightarrow ATP$
    d. $ATP \longrightarrow ADP + P$
    e. $H_2O \longrightarrow O_2 + H$
2. In an experiment, mice were fed glucose ($C_6H_{12}O_6$) containing a small amount of radioactive oxygen. The mice were closely monitored, and in a few minutes radioactive oxygen atoms showed up in
    a. CO_2.
    b. NADH.
    c. H_2O.
    d. ATP.
    e. O_2.
3. In a second experiment, mice were allowed to breathe oxygen gas (O_2) laced with radioactive oxygen. In this experiment, the radioactive oxygen atoms quickly showed up in
    a. CO_2.
    b. NADH.
    c. H_2O.
    d. ATP.
    e. glucose, $C_6H_{12}O_6$.
4. A chemist has discovered a drug that blocks glucose phosphate isomerase, an enzyme that catalyzes the second reaction in glycolysis. He wants to use the drug to kill bacteria in people with infections. But he can't do this because
    a. bacteria are facultative anaerobes; they usually don't need to do glycolysis.
    b. glycolysis produces so little ATP that the drug will have little effect.
    c. human cells also do glycolysis; the drug might also poison them.
    d. bacteria do not perform glycolysis.
    e. glycolysis can occur without the action of enzymes.
5. A glucose molecule is completely broken down in glycolysis and the Krebs cycle, but these two processes yield only a few ATPs. Where is the rest of the energy the cell obtains from the glucose molecule?
    a. in FAD and NAD^+
    b. in the oxygen used in the electron transport chain
    c. lost as heat
    d. in NADH and $FADH_2$
    e. in the CO_2 molecules released by the processes
6. Which of the following contains energy that a cell could use to make ATP?
    a. O_2
    b. CO_2
    c. NAD^+
    d. NADH
    e. H_2O
7. NADH is sometimes used by the cell in biosynthesis of needed organic molecules. Based on what you know about NADH, which of the following might be its function in biosynthesis?
    a. oxidizing organic molecules
    b. aiding in direct phosphorylation
    c. reducing organic molecules
    d. producing NAD^+
    e. breaking down ATP

8. Gram for gram, sugars are not as good as fats as a source of energy for cellular respiration, because sugars
   a. produce toxic amino groups when broken down.
   b. contain more hydrogen.
   c. usually bypass glycolysis and the Krebs cycle.
   d. contain fewer hydrogen atoms and electrons.
   e. are not as easily reduced.
9. A microbiologist discovered a new antibiotic that slowed the growth of bacteria by interfering with cellular respiration. She found that bacteria treated with the antibiotic produced about 15 ATP molecules for every glucose molecule they consumed. Which of the following hypotheses could explain the antibiotic's effect? The treated bacteria
   a. cannot perform glycolysis.
   b. have partially crippled electron transport chains.
   c. cannot produce NADH.
   d. have to rely at least partially on biosynthesis for their ATP.
   e. are forced to rely on fermentation for ATP.
10. A drug that blocks dehydrogenase enzymes would cause cells to
    a. run out of NADH.
    b. suffocate.
    c. deplete their supply of ADP.
    d. rely totally on electron transport and chemiosmosis for energy.
    e. be poisoned by lactic acid.
11. Unlike turkey breast, the breast of a duck is "dark meat." Why?
    a. Ducks fly longer distances, so their breast muscles consist of fast fibers.
    b. Ducks fly faster than turkeys, so duck breast muscles consist of fast fibers.
    c. The fibers of duck breast muscles contain less myoglobin.
    d. Ducks fly longer distances, so their breast muscles consist of slow fibers.
    e. Duck muscle fibers are specialized for anaerobic ATP production.

Essay

1. Fermentation is a much less efficient way to make ATP than aerobic cellular respiration. This being the case, why do you think the fermenters have not been driven to extinction by competition with aerobes?
2. Without oxygen, cellular respiration grinds to a standstill, although glycolysis can continue to make some ATP anaerobically for a short time. When oxygen runs out, why does electron transport stop? Why do you think the Krebs cycle stops?
3. FAD and NAD^+ are made from the B vitamins riboflavin and niacin. Why do you think these substances are required in such tiny amounts in your diet? How would a deficiency in one of these vitamins interfere with cell function?
4. After a biochemical analysis of the victim's tissues, brilliant biologist/criminal investigator J. C. Mickleberry announced his findings: "Contrary to the conclusions of the police, the victim did not suffocate. The electron carriers in his mitochondria were all in the oxidized state. We will need to perform a second autopsy to determine the actual cause of death." Explain how the data led Mickleberry to his conclusion.
5. A microbiologist poured a test tube full of yeast into a flask of sugar water and periodically took samples from the flask. At first, the amount of sugar in the flask decreased gradually. Then there was a sharp drop in sugar, accompanied by the appearance of ethanol in the flask. Explain these results.

Extending Your Knowledge

1. Look around your home and find as many products as possible that either contain yeast or were made by yeast. Why were yeasts used to make these products?
2. Health and fitness experts recommend 20 minutes of aerobic exercise at least three times a week for peak cardiovascular conditioning and weight control. What kinds of exercise do you do? Do you exercise enough?