Focus on the Concepts
This chapter discusses the roles of membranes, energy transformations, and enzymes in the functioning of cells. As you study the chapter, focus on the following concepts:

- Membranes are fluid mosaics of phospholipids and proteins. The phospholipids form a hydrophobic bilayer that is selectively permeable. Membrane proteins carry out many functions, such as transport and cell-cell recognition.

- Molecules may diffuse across a membrane in a process called passive transport. Diffusion of water through a selectively permeable membrane is called osmosis; osmosis and water balance are important to living things.

- Transport proteins may facilitate diffusion of a solute across a membrane or expend energy to actively transport a solute against its concentration gradient. Endocytosis and exocytosis can transport particles and bulk materials into and out of cells.

- Energy is the ability to do work. Kinetic energy is energy of movement. Potential energy is energy stored in position or chemical structure. Chemical reactions may release or store energy. ATP shuttles energy from energy-producing to energy-consuming processes and drives cellular work.

- An enzyme is a protein (or sometimes an RNA molecule) that speeds up a specific chemical reaction by lowering activation energy needed to start the reaction. The enzyme’s active site fits a specific substrate. Environmental conditions affect the enzyme. Inhibitors may block it and cofactors may assist it. Many drugs, pesticides, and poisons are enzyme inhibitors.

Review the Concepts
Work through the following exercises to review the concepts in this chapter. For additional review, check out the activities at www.masteringbiology.com. The website offers a pre-test that will help you plan your studies.
Review membrane structure and function by labeling the diagram of the membranes of two adjacent cells on the following image. Starting outside the cells, label a fiber of the extracellular matrix (ECM) and a signaling molecule. Inside the cells, label the cytoplasm and a microfilament of the cytoskeleton. In the membranes, find a phospholipid molecule, a cholesterol molecule, and a glycoprotein. Finally, identify protein molecules carrying out these functions: Cell-cell recognition, enzymatic activity, transport, intercellular junction, signal transduction, receptor, and attachment to the cytoskeleton and ECM. (You will note that this diagram is slightly different from Figure 5.1, so be careful!)
Exercise 2 (Modules 5.3–5.9)

Review diffusion and the function of cell membranes by matching each of the phrases on the left with the appropriate mechanisms from the list on the right. Two questions require more than one answer.

| 1. Diffusion across a membrane | A. Diffusion |
| 2. Moves solutes against concentration gradient | B. Active transport |
| 3. Any spread of particles from area of higher concentration to area of lower concentration | C. Osmosis |
| 4. Diffusion with the help of a transport protein | D. Phagocytosis |
| 5. Three types of endocytosis | E. Passive transport |
| 6. Engulfing of fluid in membrane vesicles | F. Facilitated diffusion |
| 7. Diffusion of water across selectively permeable membrane | G. Pinocytosis |
| 8. Involves transport molecules that need ATP to function | H. Receptor-mediated endocytosis |
| 9. Enables cell to engulf bulk quantities of specific large molecules | I. Exocytosis |
| 10. How oxygen and carbon dioxide enter and leave cells | |
| 11. Causes plant cell to become turgid | |
| 12. Engulfing of particle or object in membrane vesicle | |
| 13. Fusion of membrane-bound vesicle with membrane, and dumping of contents outside cell | |
| 14. How a cell might capture a bacterium | |
| 15. Helped by aquaporins | |
| 16. Causes cream to mix with coffee | |
| 17. Occurs from a hypotonic to a hypertonic solution | |
| 18. Two types of passive transport | |
| 19. Occurs when Golgi apparatus exports proteins | |
| 20. How a cell maintains a higher $K^+$ concentration and lower $Na^+$ concentration than its surroundings | |

Exercise 3 (Modules 5.4–5.5)

Osmosis is an important process that has many effects on living things. Test your understanding of osmosis by predicting in each of the following cases whether water will enter the cell (In) or leave the cell (Out), or whether there will be no net movement of water (None). Assume that the plasma membrane is permeable to water but not solutes.

| 1. Cell is exposed to a hypertonic solution. | |
| 2. Cell is placed in a salt solution whose solute concentration is greater than that of the cell contents. | |
| 3. Due to disease, the solute concentration of the body fluid outside a cell is less than the solute concentration inside cells. | |
| 4. Cell is immersed in an isotonic solution. | |
| 5. A single-celled organism is placed in a drop of pure water for examination under a microscope. | |
| 6. Cell is immersed in solution of sucrose and glucose whose individual concentrations are less than concentration of solutes in cytoplasm, but whose combined concentration is greater than concentration of solutes in cytoplasm. | |
| 7. Solute concentration of a cell is greater than the solute concentration of the surrounding fluid. | |
| 8. Cell is exposed to a hypotonic solution. | |
9. Concentration of solutes in a cell's cytoplasm equals the solute concentration of extracellular fluid.

10. Cytoplasm is more dilute than surrounding solution.

Try to picture membranes and their functions close-up by completing the following story.

Your first mission as a Bionaut requires you to enter a blood vessel and observe the structure and functions of cell membranes. You step into the water-filled chamber of the Microtron, which quickly shrinks you to a size much smaller than a red blood cell.

You tumble through the tunnel-like needle and into a blood vessel in the arm of a volunteer. Huge, rubbery red blood cells slowly glide past. Floating in the clear, yellowish blood plasma, you switch on your headlamp and examine the epithelial cells of the vessel wall. Their plasma membranes seem made of millions of small balloons. These are the hydrophilic "heads" of the 1 molecules that make up most of the membrane surface. Through the transparent surface, you can see their flexible "tails" projecting inward toward the interior of the membrane and beyond them an inner layer of 2 molecules with their tails pointing toward you. Here and there are globular 3 molecules embedded in the membrane; some rest lightly on the surface, but most project all the way into the interior of the cell. The membrane is indeed a 4 mosaic; the proteins are embedded like the pieces of a picture, but you can see that they are free to move around. You push on one of the proteins, and it bobs like an iceberg. Some of the proteins have chains of sugar molecules attached to them, forming 5 . These are the molecules that act as cell 6 tags. You notice that one of the proteins has a dimple in its surface. Just then a small, round molecule floating in the plasma nestles in the dimple. The molecule is a hormone, a chemical signal, and the dimpled protein is the 7 that enables the cell to respond to it. The signal is relayed through another protein projecting into the inside of the cell, an example of signal 8 .

In your light beam, you can see the sparkle and shimmer of many molecules, large and small, in the blood and passing through the cell membrane. Oxygen is moving from the plasma, where it is more concentrated, to the cell interior, where it is less concentrated. This movement is 9 ; when it occurs through a biological membrane, it is called 10 transport. Similarly, carbon dioxide is flowing out of the cell, down its 11 gradient, from the cell interior, where it is 12 concentrated, to the blood, where it is 13 concentrated.

You note that water molecules are passing through the membrane equally in both directions, many of them through protein channels called 14 . The total concentration of solutes in the cell and in the blood must be equal; the solutions must be 15 . You signal the control team to inject a small amount of concentrated salt solution into the blood, making the blood slightly 16 relative to the cell contents. This causes water to flow 17 the cell, until the two solutions are again in equilibrium. This diffusion of water through a 18 permeable membrane is called 19 .

Some sugar molecules floating in the blood are simply too large and polar to pass easily through the plasma membrane. The sugar molecules simply bounce off, unless
they happen to pass through pores in special proteins. This is a type of passive transport, because the molecules move down a concentration gradient without the expenditure of . Because transport proteins help out, it is called diffusion.

Your chemscanner detects a high concentration of potassium ions inside the cell. Transport proteins here and there in the membrane are able to move potassium into the cell against the concentration gradient. This must be transport; the cell expends to provide energy to "pump" the potassium into the cell.

Suddenly there is a tug at your foot. You look down to see your swim fins engulfed by a rippling membrane. A white blood cell the size of a house quickly pins you against the vessel wall! The phospholipids of its membrane are pressed against your face mask. The cell is engulfing you, protecting the body from a foreign invader! Taking in a substance in this way is called , more specifically , if the substance is a solid particle. Not fun if you are the particle! Suddenly the pressure diminishes, and you are inside the white blood cell, floating free in a membrane-enclosed bag, or . Another sac is approaching; it is a , full of digestive enzymes. You manage to get your legs outside of the vacuole and move it back toward the inner surface of the cell membrane. As the vacuole fuses with the plasma membrane, you tear your feet free and swim away from the voracious cell, realizing that expelled you almost as fast as endocytosis trapped you!

You swim to the exit point, and the control team removes you by syringe. You are soon back in the lab, restored to normal size, and telling your support team about your close call.

Exercise 5 (Modules 5.10–5.13)

After reading Modules 5.10–5.13, review energy, chemical reactions, and the function of enzymes by filling in the blanks in the following story.

If you were to stop eating, you would probably starve to death in weeks or months. If you were unable to breathe, you would die in minutes. Organisms need the energy that is released when food and oxygen combine. This energy is used not only to move the body but also to keep it from falling apart.

Energy is the ability to cause change or perform energy, energy of movement. In the process of photosynthesis, plants are able to use the energy of sunlight to produce food molecules. This process obeys the laws of , the principles that govern energy transformations. Plants do not make the energy in food. According to the law of thermodynamics, energy can be and transferred, but it cannot be created or destroyed. In photosynthesis, no energy is created. Rather, the plant carries out a series of steps that transform the energy of sunlight into chemical energy, a form of energy, stored in the chemical bonds of molecules of glucose.

No energy change is 100% efficient, and the changes that occur in photosynthesis are no exception to this rule. Some of the energy of sunlight is not stored in glucose, but rather is converted to , which is random molecular motion. This
energy is "lost" as far as the plant is concerned, and this random motion contributes to the
disorder of the plant's surroundings. The 8th law of thermodynamics
says that energy changes are always accompanied by an increase in 9,
a measure of disorder. One of the reasons living things need a constant supply of energy is
to counter this natural tendency toward disorder.

The products of photosynthesis contain more potential energy than the
10. This means that, overall, photosynthesis is an 11 reaction. Such a reaction consumes energy, which in photosynthesis is supplied by the sun.

Photosynthesis produces food molecules, such as glucose, which store energy.
An animal might obtain this food by eating a plant or an animal that has eaten a plant.
The food molecules enter the animal's cells, where their potential energy is released in the
process of cellular respiration. The products of this chemical reaction (actually a series of
reactions) contain less potential energy than the reactants. Therefore, cellular respiration is
an 12 reaction; it 13 energy. In fact, this is the same
overall change that occurs when glucose in a piece of wood or paper burns in air. When
paper burns, the energy escapes as the heat and light of the flames. In a cell, the reaction
occurs in a more controlled way, and some of the energy is captured for use by the cell.

Energy released by the exergonic "burning" of glucose in cellular respiration is
used to make a substance called 14. A molecule of 15 and a 16 group are joined to form each molecule of ATP. This is an
endergonic reaction, because it takes energy to assemble ATP. The covalent bond connecting
the phosphate group to the rest of the ATP molecule is unstable and easily broken. This
arrangement of atoms stores 17 energy. The 18 of ATP is an exergonic reaction. When ATP undergoes hydrolysis, a 19 is
removed, ATP becomes 20 , and energy is released. Thus, ATP is a kind
of energy "currency" that can be used to perform cellular 21. There are
three kinds of cellular work: 22, 23, and
24. Most cellular activities depend on ATP energizing other molecules
by transferring its phosphate group to them—a process called 25. This
happens in mechanical work, when ATP causes molecules in muscle cells to move. It should
be noted that energy is not destroyed when ATP is used to do work. When an ATP molecule
is hydrolyzed to make muscles move, some of its energy moves the body, and some ends
up as random molecular motion, or 26. Similarly, ATP is used to move
substances through 27; this is called transport work.

A less obvious but important function of ATP is supplying the energy for fighting
the natural tendency for a system to become disordered. A cell constantly needs to manufacture
molecules to replace ones that are used up or damaged. This is chemical work. Building
a large molecule from smaller parts is an 28 reaction. Energy released by
the exergonic hydrolysis of ATP is used to drive essential endergonic reactions. The linking
of exergonic and endergonic processes is called energy 29, and ATP is
the critical connection between the processes that release energy and those that consume it.

Molecules can break down; that is why ATP energy is needed to repair them.
What prevents a molecule of glucose, or even ATP itself, from breaking down until its
energy is needed? Fortunately for living things, it takes some additional energy, called
energy of 30, to get a chemical reaction started. This creates an energy
31 that prevents molecules from breaking down without a little
“push.” Energy barriers exist for both exergonic and endergonic reactions. Most of the time, most molecules in a cell lack the extra energy needed to clear the barrier, so chemical reactions occur slowly, if at all.

So what enables the vital reactions of metabolism to occur when and where they are needed, at a rate sufficient to sustain life? This is where enzymes come in. An enzyme is a special molecule that acts as a biological catalyst. It the rate of a chemical reaction without being by it. An enzyme does not add activation; rather, the enzyme holds the reactants in such a way as to the energy barrier that prevents them from reacting. Even though reactants would not normally possess the activation energy needed to start the reaction, the enzyme creates conditions that make the reaction possible. Enzymes enable the cell to carry out vital chemical changes when and where they are needed, enabling it to control the many chemical reactions that make up cellular

Exercise 6: (Modules 5.10–5.13)

Briefly summarize the differences between the words or phrases in each of the following sets.

1. Kinetic energy and potential energy

2. Exergonic reactions and endergonic reactions

3. Reactants and products

4. ATP and ADP

5. A reaction without an enzyme and a reaction with an enzyme

6. Photosynthesis and cellular respiration

7. First and second laws of thermodynamics

8. Mechanical, transport, and chemical work
Review enzyme action by completing the activities that follow.

1. Complete the diagram that follows so that it shows the cycle of enzyme activity. Imagine that the reaction carried out by this enzyme is splitting a substrate molecule into two parts. Color the diagram as suggested, and label the items in **boldface** type. Color the enzyme purple. Sketch the **substrate** as a dark blue shape. Sketch the **products**, and color them light blue. Also label the **active site**.

![Diagram](image)

2. Make a sketch showing how heat or change in pH might change the enzyme and alter its ability to catalyze its chemical reaction. Color and label the **enzyme**, its **active site**, and its **substrate**, as in question 1.

3. On the left side of the space that follows, make a sketch showing how a competitive inhibitor might interfere with activity of the enzyme. Label the **competitive inhibitor**, and color it red. On the right side, make a sketch showing how a noncompetitive inhibitor might interfere with activity of the enzyme. Label the **noncompetitive inhibitor**, and color it yellow.
Test Your Knowledge

Multiple Choice

1. The movement of molecules from an area of higher concentration to an area of lower concentration is called
   a. diffusion.
   b. endocytosis.
   c. catalysis.
   d. active transport.
   e. osmosis.

2. Which of the following is not true of an enzyme?
   An enzyme
   a. is usually a protein.
   b. acts as a biological catalyst.
   c. supplies energy to start a chemical reaction.
   d. is specific.
   e. lowers the energy barrier for a chemical reaction.

3. The most abundant molecules in cell membranes are
   a. cholesterol.
   b. phospholipids.
   c. glycolipids.
   d. proteins.
   e. enzymes.

4. In osmosis, water always moves toward the __ solution, that is, toward the solution with the __ solute concentration.
   a. isotonic . . . greater
   b. hypertonic . . . greater
   c. hypertonic . . . lesser
   d. hypotonic . . . greater
   e. hypotonic . . . lesser

5. Which of the following enables a cell to pick up and concentrate a specific kind of molecule?
   a. passive transport
   b. diffusion
   c. osmosis
   d. receptor-mediated endocytosis
   e. pinocytosis

6. A cell uses energy released by ____ reactions to drive the ____ reactions that make ATP. Then it uses the energy released by the hydrolysis of ATP, an ____ reaction, to do various kinds of work in the cell.
   a. exergonic . . . exergonic . . . endergonic
   b. endergonic . . . exergonic . . . endergonic
   c. exergonic . . . endergonic . . . exergonic
   d. endergonic . . . endergonic . . . exergonic
   e. exergonic . . . endergonic . . . endergonic

7. Activation energy
   a. is released when a large molecule breaks up.
   b. gets a reaction going.
   c. is released by an exergonic reaction.
   d. is stored in an endergonic reaction.
   e. is supplied by an enzyme.

8. The laws of thermodynamics state that whenever energy changes occur, ____ always increases.
   a. disorder
   b. order
   c. kinetic energy
   d. potential energy
   e. activation energy

9. Living things transform kinetic energy into potential chemical energy in the ____ when ____ is made.
   a. mitochondrion . . . ATP
   b. chloroplast . . . ADP
   c. chloroplast . . . an enzyme
   d. mitochondrion . . . glucose
   e. chloroplast . . . glucose

10. Why does heating interfere with the activity of an enzyme?
    a. It kills the enzyme.
    b. It changes the enzyme’s shape.
    c. It increases the energy of substrate molecules.
    d. It causes the enzyme to break up.
    e. It kills the cell, so enzymes can’t work.

11. An enzyme is specific. This means
    a. it has a certain amino acid sequence.
    b. it is found only in a certain place.
    c. it functions only under certain environmental conditions.
    d. it speeds up a particular chemical reaction.
    e. it occurs in only one type of cell.

12. Diffusion of water across a selectively permeable membrane is called
    a. active transport.
    b. osmosis.
    c. exocytosis.
    d. passive transport.
    e. facilitated diffusion.

Essay

1. Describe the kinds of molecules that cannot easily diffuse through cell membranes. How do proteins facilitate diffusion of these substances?

2. Make a sketch showing why an enzyme acts only on a specific substrate.
3. Most enzyme-catalyzed chemical reactions in humans occur most readily around body temperature, 37°C. Why do these reactions slow down at lower temperatures? Why do they slow down at higher temperatures?

4. Which contains more potential energy, a large, complex molecule like a protein, or the smaller amino acid subunits of which it is composed? Is the joining of amino acids to form a protein an exergonic or endergonic reaction? Why must this be the case? Where does the cell obtain energy to carry out such reactions?

5. Describe the circumstances under which plant and animal cells gain and lose water by osmosis. Which of the following is the least serious problem: water uptake by a plant cell, water loss by a plant cell, water uptake by an animal cell, or water loss by an animal cell? Why?

Apply the Concepts

Multiple Choice

1. If a cell is like a factory, then enzymes are like
   a. the plans for the factory.
   b. the machines in the factory.
   c. the power plant for the factory.
   d. the raw materials used by the factory.
   e. the walls of the factory.

2. A molecule that has the same shape as the substrate of an enzyme would tend to
   a. speed metabolism by guiding the enzyme to its substrate.
   b. speed metabolism by acting as a cofactor for the enzyme.
   c. speed metabolism because it would also be a catalyst.
   d. save the cell energy by substituting for the substrate.
   e. slow metabolism by blocking the enzyme’s active site.

3. A plant cell is placed in a solution whose solute concentration is twice as great as the concentration of the cell cytoplasm. The cell membrane is selectively permeable, allowing water but not the solutes to pass through. What will happen to the cell?
   a. No change will occur because it is a plant cell.
   b. The cell will shrivel because of osmosis.
   c. The cell will swell because of osmosis.

   d. The cell will shrivel because of active transport of water.
   e. The cell will swell because of active transport of water.

4. A white blood cell is capable of producing and releasing thousands of antibody molecules every second. Antibodies are large, complex protein molecules. How would you expect them to leave the cell?
   a. active transport
   b. exocytosis
   c. receptor-mediated endocytosis
   d. passive transport
   e. pinocytosis

5. Which of the following would be least likely to diffuse through a cell membrane without the help of a transport protein?
   a. a large hydrophilic molecule
   b. a large hydrophobic molecule
   c. a small hydrophilic molecule
   d. a small hydrophobic molecule
   e. Any of the above would easily diffuse through the membrane.

6. Red blood cells shrivel when placed in a 10% sucrose solution. When first placed in the solution, the solute concentration of the cells is ___ the concentration of the sucrose solution. After the cells shrivel, their solute concentration is ___ the concentration of the sucrose solution.
   a. less than . . . greater than
   b. greater than . . . less than
   c. equal to . . . equal to
   d. less than . . . equal to
   e. greater than . . . equal to

7. A nursing infant is able to obtain disease-fighting antibodies, which are large protein molecules, from its mother’s milk. These molecules probably enter the cells lining the baby’s digestive tract via
   a. osmosis.
   b. passive transport.
   c. exocytosis.
   d. active transport.
   e. endocytosis.

8. Some enzymes involved in the hydrolysis of ATP cannot function without the help of sodium ions. Sodium in this case functions as
   a. a substrate.
   b. a cofactor.
   c. an active site.
   d. a noncompetitive inhibitor.
   e. a vitamin.
9. The relationship between an enzyme's active site and its substrate is most like which of the following?
   a. a battery and a flashlight
   b. a car and a driver
   c. a key and a lock
   d. a glove and a hand
   e. a hammer and a nail

10. In which of the following do both examples illustrate kinetic energy?
    a. positions of electrons in an atom—a ball rolling down a hill
    b. heat—arrangement of atoms in a molecule
    c. a rock resting on the edge of a cliff—heat
    d. a ball rolling down a hill—heat
    e. light—arrangement of atoms in a molecule

11. Which of the following is a difference between active transport (AT) and facilitated diffusion (FD)?
    a. AT involves transport proteins, and FD does not.
    b. FD can move solutes against a concentration gradient, and AT cannot.
    c. FD requires energy from ATP, and AT does not.
    d. FD involves transport proteins, and AT does not.
    e. AT requires energy from ATP, and FD does not.

12. An enzyme and a membrane receptor molecule are similar in that they
    a. are always attached to membranes.
    b. act as catalysts.
    c. require ATP to function.
    d. supply energy for the cell.
    e. bind to molecules of a particular shape.

13. Zoologists discovered that the blood cells of a certain African lungfish were much slower to swell or shrink with water when faced with changes in blood solute concentration, a useful adaptation to drought and dehydration. The researchers suspected that this might have something to do with the number of _____ in the blood cells
    a. phospholipids.
    b. aquaporins
    c. ATPs
    d. competitive inhibitors
    e. enzymes

14. The name of which of the following tells you that it is an enzyme?
    a. folate
    b. hemoglobin
    c. kinase
    d. ribulose
    e. androstenone

15. The first enzyme in a metabolic pathway that makes ATP is blocked by ATP itself. This would appear to be an example of
    a. induced fit.
    b. energy coupling.
    c. active transport.
    d. feedback inhibition.
    e. receptor-mediated endocytosis.

Essay

1. The burning of glucose molecules in paper is an exergonic reaction, which releases heat and light. If this reaction is exergonic, why doesn’t the book in your hands spontaneously burst into flame? You could start the reaction if you touched this page with a burning match. What is the role of the energy supplied by the match?

2. Seawater is hypertonic in comparison to body tissues. Explain what would happen to his stomach cells if a shipwrecked sailor drank seawater.

3. The laws of thermodynamics have imaginatively been described as the house rules of a cosmic energy card game: “You can’t win, you can’t break even, and (if you want to stay alive) you can’t get out of the game.” State the law that says living things can’t win the energy game. State the law that says they can’t break even.

4. A farm worker accidentally was splashed with a powerful insecticide. A few minutes later he went into convulsions, stopped breathing, and died. The insecticide acted as
a competitive inhibitor of an enzyme important in the function of the nervous system. Describe the structural relationship between the enzyme, its substrate, and the insecticide molecule.

5. Lecithin is a substance used in foods such as mayonnaise as an emulsifier, which means that it helps oil and water mix. Lecithin is a phospholipid; a lecithin molecule has a polar (hydrophilic) “head” and a nonpolar (hydrophobic) “tail.” How might the structure of lecithin allow water to surround fat droplets? Sketch a microscopic view of some fat droplets in mayonnaise, and show how you think the fat, surrounding water, and lecithin molecules might be arranged.

Put Words to Work

Correctly use as many of the following words as possible when reading, talking, and writing about biology:

active site, active transport, activation energy (E_A), aquaporin, ATP, ADP, cell-cell recognition, cellular respiration, chemical energy, coenzyme, cofactor, competitive inhibitor, concentration gradient, diffusion, endergonic reaction, endocytosis, energy, energy coupling, entropy, enzyme, exergonic reaction, exocytosis, facilitated diffusion, feedback inhibition, first law of thermodynamics, fluid mosaic, glycoprotein, hypertonic solution, hypotonic solution, induced fit, isotonic solution, kinetic energy, metabolic pathway, metabolism, noncompetitive inhibitor, osmosis, osmoregulation, passive transport, phagocytosis, phospholipid, phosphorylation, photosynthesis, pinocytosis, potential energy, product, reactant, receptor, receptor-mediated endocytosis, second law of thermodynamics, selective permeability, substrate, transport, transport protein

Use the Web

There is more on membranes, energy, and enzymes at www.masteringbiology.com.
Focus on the Concepts

Cellular respiration is the process by which cells extract energy from food molecules. This process involves several steps, and there are lots of chemical details, but you can understand how it works if you focus on a few key concepts:

- There is potential energy in the arrangement of electrons in the chemical bonds of glucose and other food molecules. In a series of controlled steps, cellular respiration allows electrons to “fall” from their higher-energy positions in food molecules to oxygen, where they have lower energy. The energy of “falling” electrons is captured to make ATP, the chemical fuel for cell activities. These are redox reactions: loss of an electron is called oxidation and gain of an electron is called reduction.

- Cellular respiration occurs in three main stages: Glycolysis (which occurs in the cytoplasm of eukaryotic cells), the citric acid cycle (which occurs in the matrix of mitochondria), and oxidative phosphorylation (which is carried out along the inner membranes of mitochondria).

- Glycolysis begins the breakdown of glucose, splitting it into two molecules of pyruvate. A bit of energy is stored in ATP, and some high-energy electrons are picked up by an electron carrier called NADH, which delivers the electrons to oxidative phosphorylation. In fermentation, some cells and organisms use a modified form of glycolysis alone to make ATP without requiring oxygen.

- The products of glycolysis enter the citric acid cycle, where the step-by-step breakdown of glucose is completed. Carbon exits in CO₂. Some of the energy in the glucose is captured in a small amount of ATP. NADH and FADH₂ pick up high-energy electrons and carry them to oxidative phosphorylation.

- A series of electron carriers in the inner mitochondrial membrane carry out oxidative phosphorylation. NADH and FADH₂ from glycolysis and the citric acid cycle deliver electrons. As the electrons “fall” toward oxygen via the electron transport chain, their energy is used by carriers to pump H⁺ through the membrane. H⁺ ions build up, and as they rush back downhill through the membrane, they spin ATPase “turbines,” which manufacture most of the cell’s ATP.

- Many kinds of food molecules—carbohydrates, fats, and proteins—can be “burned” in cellular respiration to make ATP. Conversely, many molecular fragments are formed as food is broken down in cellular respiration; these can be used to construct carbohydrates, fats, and proteins that cells need.