CHAPTER 5

The Working Cell

Objectives

Introduction Describe the basic mechanism of light production in fireflies.

Energy and the Cell

5.1 Define and compare kinetic energy, potential energy, chemical energy, and heat.
5.2 Define the first and second laws of thermodynamics. Explain how the nature of energy transformations is guided by these laws of thermodynamics.
5.3 Define and compare endergonic and exergonic reactions. Explain how cells use these reactions to survive.
5.4 Explain how ATP functions as an energy shuttle.

How Enzymes Work

5.5 Explain how enzymes speed up chemical reactions.
5.6 Describe the structure of an enzyme-substrate interaction.
5.7 Explain how the cellular environment affects enzyme activity.
5.8 Explain how competitive and noncompetitive inhibitors alter an enzyme's activity.
5.9 Explain how certain pesticides and antibiotics work by inhibiting enzymes.

Membrane Structure and Function

5.10 Explain how membranes help organize the chemical activities of a cell.
5.11 Relate the structure of phospholipid molecules to the structure and properties of cell membranes.
5.12 Describe the fluid mosaic structure of cell membranes.
5.13 Describe the diverse functions of membrane proteins.
5.14–5.15 Describe the process of passive transport. Explain why osmosis is the passive transport of water.
5.15 Distinguish between hypertonic, hypotonic, and isotonic solutions.
5.16 Explain how plant and animal cells change when placed into a hypertonic or hypotonic solution.
5.17–5.18 Compare the processes of facilitated diffusion and active transport.
5.19 Distinguish between exocytosis, endocytosis, phagocytosis, pinocytosis, and receptor-mediated endocytosis.
5.20 Describe the cause of hypercholesterolemia.
5.21 Describe the central role of chloroplasts and mitochondria in harvesting energy and making it available for cellular work.

Key Terms

energy
kinetic energy
heat
potential energy
chemical energy
thermodynamics
first law of thermodynamics
second law of thermodynamics
entropy
endergonic reaction
exergonic reaction
cellular respiration
cellular metabolism
ATP
energy coupling
phosphorylation
energy of activation (E_A)
enzyme
substrate
active site
cofactor
coenzyme
competitive inhibitor
noncompetitive inhibitor
negative feedback
selective permeability
fluid mosaic
receptor
signal transduction
diffusion
passive transport
concentration gradient
osmosis
hypertonic
hypotonic
isotonic
osmoregulation
facilitated diffusion
active transport
exocytosis
endocytosis
phagocytosis
pinocytosis
receptor-mediated endocytosis
hypercholesterolemia

Word Roots

endo- = within (*endergonic reaction:* a reaction that absorbs free energy from its surroundings)

endo- = inner; **cyto-** = cell (*endocytosis:* the movement of materials into a cell. Cell-eating.)

ex- = out (*exergonic reaction:* a reaction that proceeds with a net release of free energy)

hyper- = exceeding; **-tonus** = tension (*hypertonic:* a solution with a higher concentration of solutes)

hypo- = lower (*hypotonic:* a solution with a lower concentration of solutes)

Lecture Outline

Introduction *Cool "Fires" Attract Mates and Meals*

A. Characteristics of organisms (the light of a firefly, the red pigments of a New England autumn, the trumpeting of an elk, the rank odor of mildew in a damp closet) are all the end products of chemical reactions that occur in organisms and their cells.

B. Organisms carry out chemical reactions for the purpose of energy transformation. In fact, all reactions involve some energy transformation.

C. This chapter covers several topics involved in how cells actually perform work: energy, enzymes, and membranes.
Preview: Some reactions are simply required for biosynthesis (for example, the digestion of food into smaller parts, the formation of pigments, the release of smelly waste products). Biosynthesis is discussed further in Module 6.17.

I. Energy and the Cell

Module 5.1 Energy is the capacity to perform work.

A. **Energy** can only be described and measured by how it affects matter. There are two forms of energy.

B. **Kinetic energy** is the energy of motion. Heat is the kinetic energy associated with randomly moving molecules. The energy in light is another form of kinetic energy (talk about capturing energy from light during photosynthesis).

C. **Potential energy** is the stored capacity to perform work. The most important form of potential energy in living things is the potential energy stored in the arrangement of atoms in molecules. This is called **chemical energy.**
NOTE: Some everyday examples help clarify these early definitions, such as Figure 5.1A and B, or diagrams of water flowing downhill, dammed up, and flowing through a turbine or over a waterwheel.

Module 5.2 Two laws govern energy conversion.

A. Thermodynamics is the study of energy transformation that occurs in matter.
Preview: As discussed in Module 36.8, there is a limit to the length of a food chain. These limits are the direct result of the laws of thermodynamics.

B. **First law of thermodynamics** (energy conservation). The total amount of energy in the universe is constant; this energy can be transferred or transformed but neither created nor destroyed (Figure 5.2A). When a quantity of gasoline is ignited in the confines of a gasoline engine, the chemical energy ends up in three places: unspent chemical energy in unused gasoline, which exits in the exhaust; kinetic energy of the spinning engine; and heat. (This relates to the second law.)

C. **Second law of thermodynamics** (entropy increases). Every energy change results in increased disorder, or increased **entropy** (when looking at the state of the energy throughout the system studied). When a quantity of gasoline is ignited, its potential (chemical energy) is released, causing a flash of light and burst of heat, which heats up the surrounding environment (Figure 5.2B).

D. Biological systems function in much the same way; although some chemical energy may be channeled into useful work, there is always an increase in disorder. This is almost always an increase in the kinetic energy of molecules in cells (heat).

Module 5.3 Chemical reactions either store or release energy.

A. **Endergonic reactions** require an input of energy equal to the difference in the potential energy of the reactants and products (Figure 5.3A).

B. *Preview:* Photosynthesis (Chapter 7) is an important process that is endergonic, using the energy of sunlight to form organic compounds.

C. **Exergonic reactions** result in an output of energy equal to the difference in the potential energy of the reactants and products (Figure 5.3B).

D. Burning and **cellular respiration** are both exergonic processes by which the chemical energy of the reactants is released to form energy-poor products. In the case of burning, this happens all at once, with much "waste" of the chemical energy (gasoline, for example) to form heat and light.

E. *Preview:* Cellular respiration (Chapter 6) is an important biological process that releases the potential energy of fuel molecules (carbohydrates, lipids, proteins) slowly, to form some energy-poor reactants, and, most important, to convert the chemical energy of fuel molecules into smaller, usable amounts of chemical energy in the form of ATP (Module 5.4).

F. **Cellular metabolism** is the sum total of all the endergonic and exergonic reactions in cells.

Module 5.4 ATP shuttles chemical energy within the cell.

A. Most endergonic cellular reactions require small amounts of energy, rather than the large amounts of energy available in food storage molecules.

B. Even a single glucose molecule contains too much energy. It's like a $50 or $100 bill: you want some $10s or $1s.

C. **Adenosine triphosphate (ATP)** is the energy-rich, spendable, "energy small change" of cellular reactions. It transfers usable amounts of energy from exergonic, food energy-releasing reactions to the endergonic reactions where cell work is done.

D. Various covalent bonds link the atoms in the parts of ATP, but the terminal bonds connecting the outer two phosphate parts are, at once, energy-rich and easily broken by hydrolysis.

E. The hydrolysis of ATP to release some of its chemical energy is an exergonic reaction (Figure 5.4A).

F. When ATP gives up its energy, it forms ADP and an energy shuttle, the phosphate group (Figure 5.4B).

G. The phosphate group is one of the reactants and the energy source for an endergonic reaction. This energizing process is known as phosphorylation. The products of the reaction hold chemical energy and are ready to do work.

H. ATP regeneration is the reverse process. Endergonic reactions involved in cellular respiration **phosphorylate** (and energize) ADP in dehydration synthesis.

I. ATP is constantly being regenerated and used in a cycle involving endergonic dehydration synthesis and exergonic hydrolysis (Figure 5.4C).

II. How Enzymes Work

Module 5.5 Enzymes speed up the cell's chemical reactions by lowering energy barriers.

A. **Enzymes** are large protein molecules that function as biological catalysts. A catalyst is a chemical that speeds up the reaction without itself being consumed (Figure 5.5A, B). *NOTE:* Enzyme names end in *-ase* and are often named after their substrates. For example, the enzyme that catalyzes the hydrolysis of sucrose is sucrase. Ask the students if they know anyone who can't drink milk (lactose intolerance and lactase deficiency).

B. The **energy of activation** is the amount of energy, an "energy barrier," that must be put into an exergonic reaction before the reaction will proceed (analogy of the Mexican jumping beans, Figure 5.5A; energy diagram, Figure 5.5B).

Module 5.6 A specific enzyme catalyzes each cellular reaction.

A. The reactant in an enzyme-catalyzed reaction is the **substrate.**

B. One part of the enzyme binds to the substrate at the **active site,** holding the substrate in a specific position that facilitates the reaction (Figure 5.6).

C. At the end of the reaction, the substrate changes into the product and is released, and the enzyme is unchanged.

Module 5.7 The cellular environment affects enzyme activity.

A. Factors such as temperature, pH, salt concentration, and the presence of **cofactors** often affect the way enzymes work.
Preview: Magnesium is a cofactor that is essential for the proper functioning of chlorophyll (Module 32.6).

B. Organic cofactors are called **coenzymes.**
Preview: Vitamins are coenzymes (Chapter 21, Module 21.17).

Module 5.8 Enzyme inhibitors block enzyme action.

A. Inhibitors work by binding with the active site **(competitive inhibitors)** or some other site **(noncompetitive inhibitors)** on the enzyme, thus affecting the enzyme's ability to bind with the substrate (Figure 5.8).

B. **Negative feedback** is a type of inhibition whereby enzyme activity is blocked by one of the products of the reaction it catalyzes.
NOTE: Negative feedback mechanisms are of major importance in the regulation of biological systems. A very clear example of this is seen in the regulation of female and male reproductive systems (Chapter 27).

Module 5.9 Connection: Some pesticides and antibiotics inhibit enzymes.

A. For example, the pesticide malathion inhibits the enzyme acetylcholinesterase, involved in nerve transmission.

B. The antibiotic penicillin interferes with an enzyme that helps build bacterial cell walls.

III. Membrane Structure and Function

Module 5.10 Membranes organize the chemical activities of cells.

A. Membranes separate cells from the outside environments, including, in multicellular organisms, the environment in other cells that perform different functions.

B. Membranes control the passage of molecules from one side of the membrane to the other.

C. In eukaryotes, membranes partition function into organelles.

D. Membranes provide reaction surfaces, and organize enzymes and their substrates.
Preview: The electron transport chain and chemiosmosis (Figures 6.7A, 6.12, and 7.9).

E. Membrane thickness cannot be seen in sections under the light microscope. Membranes can be resolved in TEM micrographs (Figure 5.10).

Module 5.11 Membrane phospholipids form a bilayer.

A. Phospholipids are like fats, with two nonpolar fatty acid "tails" and one polar phosphate "head" attached to the glycerol (Figure 5.11A).

B. In water, thousands of individual molecules form a stable bilayer, aiming their heads out and their tails in (Figure 5.11B).

C. The hydrophobic interior of this bilayer offers an effective barrier to the flow of most hydrophilic molecules, but allows the passage of hydrophobic molecules.

Module 5.12 The membrane is a **fluid mosaic** of phospholipids and proteins.

A. It is a mosaic because the proteins form a "tiled pattern" in the "grout ground" of the phospholipid bilayer (Figure 5.12).

B. It is fluid (like salad oil) because the individual molecules are more or less free to move about laterally.

C. The two sides of the membrane usually incorporate different sets of proteins: glycoproteins and glycolipids.

D. Some proteins extend through both sides of the bilayer and bind to the cytoskeleton and/or the extracellular matrix.
NOTE: Cholesterol is a common constituent of animal cell membranes and stabilizes membrane fluidity at different temperatures (Figure 5.12). So, cholesterol is not always "bad."

Module 5.13 Proteins make the membrane a mosaic of function.

A. Identification tags: particularly glycoproteins (and nonprotein-containing glycolipids) (Figure 5.12).

B. Enzymes: catalyzing intracellular and extracellular reactions (Figure 5.13A).

C. Receptors: triggering cell activity when a messenger molecule attaches (e.g., signal transduction; Figure 5.13B).
Preview: **Signal transduction** (Module 11.13).

D. Cell junctions: either attachments to other cells or the internal cytoskeleton.

E. Transporters: of hydrophilic molecules (Figure 5.13C).

Module 5.14 Passive transport is diffusion across a membrane.

A. **Diffusion** is the tendency for particles of any kind to spread out spontaneously from an area of high concentration to an area of low concentration.
NOTE: A concentration gradient is a form of potential energy. The movement of the molecules is kinetic energy.

B. **Passive transport** across membranes occurs (as diffusion does everywhere) when a molecule diffuses down a **concentration gradient.** At equilibrium, molecules continue to diffuse back and forth, but there is no net change in concentration anywhere (Figure 5.14A).

C. Different molecules diffuse independently of one another (Figure 5.14B).

D. Passive transport is an extremely important way for small molecules to get into and out of cells. For example, O_2 moves into red blood cells and CO_2 moves out of these cells by this process in the lungs.

Module 5.15 Osmosis is the passive transport of water (Figure 5.15A, B).

A. If a membrane that is permeable to water but not to a solute separates an area of high solute concentration **(hypertonic)** from an area of low solute concentration **(hypotonic),** the water diffuses by **osmosis** to the hypertonic area until the concentration of each solute is the same on both sides of the membrane.
NOTE: Osmosis can cause a physical force to be applied to the hypertonic solution. In the case shown in Figure 5.15, this osmotic force raises the level of the solution on the right against the force of gravity, until the weight difference in levels equals the osmotic force.

B. The direction of osmosis is determined only by the difference in total solute concentrations.

C. Two solutions equal in solute concentrations are **isotonic** to each other; therefore osmosis does not occur.

D. However, even in isotonic solutions separated by a selectively permeable membrane, water molecules are moving at equal rates in both directions.

Module 5.16 Water balance between cells and their surroundings is crucial to organisms.

A. Cell membranes act as selectively permeable membranes between the cell contents and its surroundings (Figure 5.16).

B. If a plant or animal cell is isotonic with its surroundings, no osmosis occurs, and the cells do not change. However, plant cells in such environments are flaccid or wilted, lacking the turgor that helps support some plant tissues.

C. An animal cell in a hypotonic solution will gain water and pop. A plant cell in a hypotonic solution will become turgid, as the cell wall counters the osmotic force of water moving in.

D. An animal cell in a hypertonic solution will lose water and shrivel. A plant cell in a hypertonic solution will lose water past the cell membrane but not the cell wall, resulting in the plasma membrane pulling away from the inside of the cell wall and the cell as a whole losing turgor.

E. *Preview:* The control of water balance, osmoregulation, is discussed in Module 25.5.

Module 5.17 Transport proteins facilitate diffusion across membranes (Figure 5.17).

A. **Facilitated diffusion** occurs when a pored protein, spanning the membrane bilayer, allows a solute to diffuse down a concentration gradient.

B. The cell does not expend energy.

C. The rate of facilitated diffusion depends on the number of such transport proteins, in addition to the strength of the concentration gradient.

D. Water is a polar molecule and therefore needs the assistance of transport proteins when crossing membranes. A good example of this are the aquaporins (water transport proteins) in the collecting ducts of the kidneys.

Module 5.18 Cells expend energy for active transport.

A. **Active transport** involves the assistance of a transport protein when moving a solute against a concentration gradient (Figure 5.18, parts 1–3).

B. Energy expenditure in the form of ATP-mediated phosphorylation is required to help the protein change its structure and thus move the solute molecule.

C. Active transport proteins often couple the passage of two solutes in opposite directions across membranes. (Figure 5.18, parts 4–6).

D. *Preview:* A very important example of a coupled active transport system is the Na^+–K^+ pump, which functions in nerve impulse transmission (Modules 28.4 and 28.5).

Module 5.19 Exocytosis and endocytosis transport large molecules.

A. In **exocytosis,** membrane-bounded vesicles containing large molecules fuse with the plasma membrane and release their contents outside the cell (Figure 5.19A).

B. In **endocytosis,** the plasma membrane surrounds materials outside the cell, closes around the materials, and forms membrane-bounded vesicles containing the materials (Figure 5.19B).

C. Three important types of endocytosis are **phagocytosis** ("cell eating"), **pinocytosis** ("cell drinking"), and **receptor-mediated endocytosis** (very specific) (Figure 5.19C).

Module 5.20 Connection: Faulty membranes can overload the blood with cholesterol (Figure 5.20).

A. Cholesterol is carried in the blood by low-density lipoprotein (LDL) particles.

B. In people with normal cholesterol metabolism, excess LDL-bound cholesterol in the blood is eliminated by receptor-mediated endocytosis by liver cells.

C. In people with a genetic condition that results in **hypercholesterolemia,** fewer or no such receptor sites exist, and the people accumulate LDL-bound cholesterol, perhaps leading to heart disease.

D. *Preview:* The genetics of this disease is discussed in Module 9.12. As discussed in Module 21.20, hypercholesterolemia can also be a result of lifestyle.

Module 5.21 Chloroplasts and mitochondria make energy available for cellular work.

A. The subjects of this chapter (energy, enzymes, and membranes) are important parts of the functioning of these two organelles and the processes they carry out (photosynthesis and cellular respiration).

B. Photosynthesis and cellular respiration are linked (Figure 5.21).

C. Solar energy is used to build energy-rich molecules in endergonic reactions in chloroplasts.
Preview: Photosynthesis is discussed in Chapter 7.

D. The energy-rich molecules release their energy to form ATP in mitochondria.
Preview: Cellular respiration is discussed in Chapter 6.

E. The chemicals involved as the reactants in chloroplasts are the products in mitochondria, and vice versa.

F. Energy, in the form of heat, is lost to the environment thus a constant supply of energy must be supplied to all organisms.

Class Activities

1. To demonstrate osmosis, take a limp piece of celery and place it in cold water (a hypotonic solution); the water will move into the celery by osmosis, and the resulting turgor pressure will stiffen the celery.
2. Have your students consider why, since they shower and bathe in hypotonic solutions, they do not fill with water and explode.
3. See if your students can relate their understanding of the material covered in this class to the childhood cruelty of putting salt on slugs.
4. Though osmoregulation will be discussed in a later chapter (Chapter 25), see if your students can think of mechanisms that would permit plants and animals to survive in either a hypertonic (saltwater) or a hypotonic (freshwater) environment.

Transparency Acetates

Figure 5.3A	Endergonic reaction (energy required)
Figure 5.3B	Exergonic reaction (energy released)
Figure 5.4A	ATP structure and hydrolysis
Figure 5.4B	How ATP powers cellular work
Figure 5.4C	The ATP cycle
Figure 5.5A	Jumping-bean analogy for energy of activation (E_A) and the role of enzymes
Figure 5.5B	The effect of an enzyme on E_A
Figure 5.6	How an enzyme works
Figure 5.8	How inhibitors interfere with substrate binding
Figure 5.11A	Phospholipid molecule
Figure 5.11B	Phospholipid bilayer
Figure 5.12	The plasma membrane of an animal cell
Figure 5.13–C	Enzyme activity; Signal transduction; Transport
Figure 5.14A	Passive transport of one type of molecule
Figure 5.14B	Passive transport of two types of molecules
Figure 5.15	Osmosis
Figure 5.16	How cells behave in different solutions
Figure 5.17	Transport protein providing a pore for solute passage
Figure 5.18	Active transport of two solutes across a membrane
Figure 5.19A	Exocytosis
Figure 5.19B	Endocytosis *(combined with Figure 5.19A)*
Figure 5.20	A cell using receptor-mediated endocytosis to take up an LDL
Figure 5.21	Energy flow and chemical recycling

Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Animations and Videos	File Name
Energy Concepts Animation	05-01-EnergyConceptsAnim.mov
How Enzymes Work Animation	05-06-HowEnzymesWorkAnim.mov
Membrane Structure Animation	05-11B-MembraneStrucAnim.mov
Receptor Proteins Animation	05-13-ReceptorProtAnim.mov
Diffusion Animation	05-14-DiffusionAnim.mov
Osmosis Animation	05-15-OsmosisAnim.mov
Plasmolyzing *Elodea* Video	05-16-PlasmolyElodeaVideo-B.mov

Plasmolyzing *Elodea* Video	05-16-PlasmolyElodeaVideo-S.mov
Elodea Video	05-16-TurgidElodeaVideo-B.mov
Elodea Video	05-16-TurgidElodeaVideo-S.mov
Active Transport Animation	05-18-ActiveTransportAnim.mov
Exocytosis/Endocytosis Introduction Animation	05-19-ExocyEndoIntroAnim.mov
Exocytosis Animation	05-19A-ExocytosisAnim.mov
Phagocytosis Animation	05-19C-PhagocytosisAnim.mov
Pinocytosis Animation	05-19C-PinocytosisAnim.mov
Receptor-Mediated Endocytosis Animation	05-19C-ReceptMedEndoAnim.mov

Activities and Thinking as a Scientist	**Module Number**
Web/CD Activity 5A: *Energy Transformations*	5.2
Web/CD Activity 5B: *Chemical Reactions and ATP*	5.3
Web/CD Activity 5C: *The Structure of ATP*	5.4
Web/CD Activity 5D: *How Enzymes Work*	5.6
Web/CD Thinking as a Scientist: *How is the Rate of Enzyme Catalysis Measured?*	5.7
Biology Labs On-Line: *EnzymeLab*	5.8
Web/CD Activity 5E: *Membrane Structure*	5.12
Web/CD Activity 5F: *Signal Transduction*	5.13
Web/CD Activity 5G: *Selective Permeability of Membranes*	5.13
Web/CD Thinking as a Scientist: *How Do Cells Communicate with Each Other?*	5.13
Web/CD Activity 5H: *Diffusion*	5.14
Web/CD Activity 5I: *Osmosis and Water Balance in Cells*	5.16
Web/CD Thinking as a Scientist: *How Does Osmosis Affect Cells?*	5.16
Web/CD Activity 5J: *Facilitated Diffusion*	5.17
Web/CD Activity 5K: *Active Transport*	5.18
Web/CD Activity 5L: *Exocytosis and Endocytosis*	5.19
Web/CD Activity 5M: *Build a Chemical Cycling System*	5.21