WHAT YOU SHOULD KNOW-   
Metabolism, Photosynthesis, & Respiration Chap 8, 9, & 10

**Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce and to maintain dynamic homeostasis.**

Enduring understanding 2.A: Growth, reproduction and maintenance of the organization of living systems require free energy and matter.

***Essential knowledge 2.A.1: All living systems require constant input of free energy.***   
 a. Life requires a highly ordered system.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*   
 1. Order is maintained by constant free energy input into the system.   
 2. Loss of order or free energy flow results in death.   
 3. Increased disorder and entropy are offset by biological processes that maintain or   
 increase order.   
 b. Living systems do not violate the second law of thermodynamics, which states that entropy   
 increases over time.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*   
 1. Order is maintained by coupling cellular processes that increase entropy (and so have   
 negative changes in free energy) with those that decrease entropy (and so have positive   
 changes in free energy).   
 2. Energy input must exceed free energy lost to entropy to maintain order and power   
 cellular processes.   
 3. Energetically favorable exergonic reactions, such as ATP→ADP, that have a negative change in free energy can be used to maintain or increase order in a system by being coupled with reactions that have a positive free energy change.

c. Energy-related pathways in biological systems are sequential and may be entered at multiple   
 points in the pathway. [See also **2.A.2**]   
 *To foster student understanding of this concept, instructors can choose an illustrative example such as:*   
 • Krebs cycle   
 • Glycolysis   
 • Calvin cycle   
 • Fermentation

d. Organisms use free energy to maintain organization, grow and reproduce.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*   
 1. Organisms use various strategies to regulate body temperature and metabolism.   
 *To foster student understanding of this concept, instructors can choose an illustrative example such as:*   
 • Endothermy (the use of thermal energy generated by metabolism to maintain   
 homeostatic body temperatures)   
 • Ectothermy (the use of external thermal energy to help regulate and maintain body   
 temperature)   
 • Elevated floral temperatures in some plant species

2. Reproduction and rearing of offspring require free energy beyond that used for   
 maintenance and growth. Different organisms use various reproductive strategies in   
 response to energy availability.   
 *To foster student understanding of this concept, instructors can choose an illustrative example such as:*   
 • Seasonal reproduction in animals and plants   
 • Life-history strategy (biennial plants, reproductive diapause)

3. There is a relationship between metabolic rate per unit body mass and the size of   
 multicellular organisms — generally, the smaller the organism, the higher the metabolic   
 rate.

4. Excess acquired free energy versus required free energy expenditure results in energy   
 storage or growth.

5. Insufficient acquired free energy versus required free energy expenditure results in loss   
 of mass and, ultimately, the death of an organism.

e. Changes in free energy availability can result in changes in population size.

f. Changes in free energy availability can result in disruptions to an ecosystem.   
 *To foster student understanding of this concept, instructors can choose an illustrative example such as:*   
 • Change in the producer level can affect the number and size of other trophic levels.   
 • Change in energy resources levels such as sunlight can affect the number and size of the   
 trophic levels.

Learning Objectives:   
**LO 2.1** The student is able to explain how biological systems use free energy based on empirical data that all organisms require constant energy input to maintain organization, to grow and to reproduce. [See **SP 6.2**]

**LO 2.2** The student is able to justify a scientific claim that free energy is required for living systems to maintain organization, to grow or to reproduce, but that multiple strategies exist in different living systems. [See **SP 6.1**]

**LO 2.3** The student is able to predict how changes in free energy availability affect organisms, populations and ecosystems. [See **SP 6.4**]

***Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.***   
 a. Autotrophs capture free energy from physical sources in the environment.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*   
 1. Photosynthetic organisms capture free energy present in sunlight.

2. Chemosynthetic organisms capture free energy from small inorganic molecules present in their environment, and this process can occur in the absence of oxygen.

b. Heterotrophs capture free energy present in carbon compounds produced by other organisms.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*   
 1. Heterotrophs may metabolize carbohydrates, lipids and proteins by hydrolysis as sources   
 of free energy.

2. Fermentation produces organic molecules, including alcohol and lactic acid, and it   
 occurs in the absence of oxygen.   
 ✘ *Specific steps, names of enzymes and intermediates of the pathways for these   
 processes are beyond the scope of the course and the AP Exam.*

c. Different energy-capturing processes use different types of electron acceptors.   
 *To foster student understanding of this concept, instructors can choose an illustrative example such as:*   
 • NADP+ in photosynthesis   
 • Oxygen in cellular respiration

d. The light-dependent reactions of photosynthesis in eukaryotes involve a series of coordinated   
 reaction pathways that capture free energy in light to yield ATP and NADPH, which power the   
 production of organic molecules.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*

1. During photosynthesis, chlorophylls absorb free energy from light, boosting electrons to a higher energy level in Photosystems I and Photosystem II.

2. Photosystems I and II are embedded in the internal membranes of chloroplasts   
 (thylakoids) and are connected by the transfer of higher free energy electrons through an   
 electron transport chain (ETC). [See also **4.A.2**]

3. When electrons are transferred between molecules in a sequence of reactions as they pass   
 through the ETC, an electrochemical gradient of hydrogen ions (protons) across the   
 thykaloid membrane is established.

4. The formation of the proton gradient is a separate process, but it is linked to the   
 synthesis of ATP from ADP and inorganic phosphate via ATP synthase.   
  
 5. The energy captured in the light reactions as ATP and NADPH powers the production   
 of carbohydrates from carbon dioxide in the Calvin cycle, which occurs in the stroma of   
 the chloroplast.  
 ✘✘ *Memorization of the steps in the Calvin cycle, the structure of the molecules and the   
 names of enzymes (with the exception of ATP synthase) are beyond the scope of the   
 course and the AP Exam.*

e. Photosynthesis first evolved in prokaryotic organisms; scientific evidence supports that   
 prokaryotic (bacterial) photosynthesis was responsible for the production of an oxygenated   
 atmosphere; prokaryotic photosynthetic pathways were the foundation of eukaryotic   
 photosynthesis.

f. Cellular respiration in eukaryotes involves a series of coordinated enzyme-catalyzed reactions   
 that harvest free energy from simple carbohydrates.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*  
 1. Glycolysis rearranges the bonds in glucose molecules, releasing free energy to form ATP   
 from ADP and inorganic phosphate, and resulting in the production of pyruvate.

2. Pyruvate is transported from the cytoplasm to the mitochondrion, where further   
 oxidation occurs. [See also **4.A.2**]

3. In the Krebs cycle, carbon dioxide is released from organic intermediates ATP is   
 synthesized from ADP and inorganic phosphate via substrate level phosphorylation and   
 electrons are captured by coenzymes.

4. Electrons that are extracted in the series of Krebs cycle reactions are carried by NADH   
 and FADH2 to the electron transport chain.   
✘✘ *Memorization of the steps in glycolysis and the Krebs cycle, or of the structures of the molecules and the names of the enzymes involved, are beyond the scope of the course and the AP Exam*

g. The electron transport chain captures free energy from electrons in a series of coupled reactions   
 that establish an electrochemical gradient across membranes.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*   
   
 1. Electron transport chain reactions occur in chloroplasts (photosynthesis), mitochondria   
 (cellular respiration) and prokaryotic plasma membranes.

2. In cellular respiration, electrons delivered by NADH and FADH2 are passed to a series |   
 of electron acceptors as they move toward the terminal electron acceptor, oxygen. In   
 photosynthesis, the terminal electron acceptor is NADP+.

3. The passage of electrons is accompanied by the formation of a proton gradient across   
 the inner mitochondrial membrane or the thylakoid membrane of chloroplasts, with the   
 membrane(s) separating a region of high proton concentration from a region of low   
 proton concentration. In prokaryotes, the passage of electrons is accompanied by the   
 outward movement of protons across the plasma membrane.

4. The flow of protons back through membrane-bound ATP synthase by chemiosmosis   
 generates ATP from ADP and inorganic phosphate.

5. In cellular respiration, decoupling oxidative phosphorylation from electron transport is   
 involved in thermoregulation.   
 ✘✘ *The names of the specific electron carriers in the ETC are beyondthe scope of the course   
 and the AP Exam.*

h. Free energy becomes available for metabolism by the conversion of ATP→ADP, which is coupled   
 to many steps in metabolic pathways.

Learning Objectives:   
**LO 2.4** The student is able to use representations to pose scientific questions about what mechanisms and structural features allow organisms to capture, store and use free energy. [See **SP 1.4, 3.1**]

**LO 2.5** The student is able to construct explanations of the mechanisms and structural features of cells that allow organisms to capture, store or use free energy. [See **SP 6.**

***Essential knowledge 4.B.1: Interactions between molecules affect their structure and function.***   
 a. Change in the structure of a molecular system may result in a change of the function of the   
 system. [See also **3.D.3**]

b. The shape of enzymes, active sites and interaction with specific molecules are essential for basic   
 functioning of the enzyme.   
 *Evidence of student learning is a demonstrated understanding of each of the following:*

1. For an enzyme-mediated chemical reaction to occur, the substrate must be complementary   
 to the surface properties (shape and charge) of the active site. In other words, the substrate   
 must fit into the enzyme's active site.

2. Cofactors and coenzymes affect enzyme function; this interaction relates to a structural   
 change that alters the activity rate of the enzyme. The enzyme may only become active   
 when all the appropriate cofactors or coenzymes are present and bind to the appropriate   
 sites on the enzyme.   
 ✘✘ *No specific cofactors or coenzymes are within the scope of the course and the AP Exam.*

c. Other molecules and the environment in which the enzyme acts can enhance or inhibit enzyme   
 activity. Molecules can bind reversibly or irreversibly to the active or allosteric sites, changing the   
 activity of the enzyme.

d. The change in function of an enzyme can be interpreted from data regarding the concentrations   
 of product or substrate as a function of time. These representations demonstrate the   
 relationship between an enzyme's activity, the disappearance of substrate, and/ or presence of a   
 competitive inhibitor.

Learning Objective:   
**LO 4.17** The student is able to analyze data to identify how molecular interactions affect structure and function. [See **SP 5.1**]

***Essential knowledge 4.B.2: Cooperative interactions within organisms promote efficiency in the use of energy and matter.***   
 a. Organisms have areas or compartments that perform a subset of functions related to energy and   
 matter, and these parts contribute to the whole. [See also **2.A.2**, **4.A.2**]   
 *Evidence of student learning is a demonstrated understanding of each of the following:*   
  
 1. At the cellular level, the plasma membrane, cytoplasm and, for eukaryotes, the organelles   
 contribute to the overall specialization and functioning of the cell.

2. Within multicellular organisms, specialization of organs contributes to the overall   
 functioning of the organism.   
 *To foster student understanding of this concept, instructors can choose an illustrative example such as:*   
 • Exchange of gases   
 • Circulation of fluids   
 • Digestion of food   
 • Excretion of wastes   
  
 3. Interactions among cells of a population of unicellular organisms can be similar to those   
 of multicellular organisms, and these interactions lead to increased efficiency and   
 utilization of energy and matter.   
 *To foster student understanding of this concept, instructors can choose an illustrative example such as:*   
 • Bacterial community in the rumen of animals  
 • Bacterial community in and around deep sea vents

Learning Objective:   
**LO 4.18** The student is able to use representations and models to analyze how cooperative interactions within organisms promote efficiency in the use of energy and matter. [See **SP 1.4**]