LO 2.7 Students will be able to explain how cell size and shape affect the overall rate of nutrient intake and the rate of waste elimination. [See **SP 6.2**]

LO 2.8 The student is able to justify the selection of data regarding the types of molecules that an animal, plant or bacterium will take up as necessary building blocks and excrete as waste products. [See **SP 4.1**]

LO 2.9 The student is able to represent graphically or model quantitatively the exchange of molecules between an organism and its environment, and the subsequent use of these molecules to build new molecules that facilitate dynamic homeostasis, growth and reproduction. [See **SP 1.1, 1.4**]

Enduring understanding 2.B: Growth, reproduction and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.

Cell membranes separate the internal environment of the cell from the external environment. The specialized structure of the membrane described in the fluid mosaic model allows the cell to be selectively permeable, with dynamic homeostasis maintained by the constant movement of molecules across the membrane. Passive transport does not require the input of metabolic energy because spontaneous movement of molecules occurs from high to low concentrations; examples of passive transport are osmosis, diffusion, and facilitated diffusion. Active transport requires metabolic energy and transport proteins to move molecules from low to high concentrations across a membrane. Active transport establishes concentration gradients vital for dynamic homeostasis, including sodium/potassium pumps in nerve impulse conduction and proton gradients in electron transport chains in photosynthesis and cellular respiration. The processes of endocytosis and exocytosis move large molecules from the external environment to the internal environment and vice versa, respectively.

Eukaryotic cells also maintain internal membranes that partition the cell into specialized regions so that cell processes can operate with optimal efficiency by increasing beneficial interactions, decreasing conflicting interactions and increasing surface area for chemical reactions to occur. Each compartment or membrane-bound organelle localizes reactions, including energy transformation in mitochondria and production of proteins in rough endoplasmic reticulum.

Essential knowledge 2.B.1: Cell membranes are selectively permeable due to their structure.

a. Cell membranes separate the internal environment of the cell from the external environment.

b. Selective permeability is a direct consequence of membrane structure, as described by the fluid mosaic model. [See also **4.A.1**]

Evidence of student learning is a demonstrated understanding of each of the following:

1. Cell membranes consist of a structural framework of phospholipid molecules, embedded proteins, cholesterol, glycoproteins and glycolipids.
2. Phospholipids give the membrane both hydrophilic and hydrophobic properties. The hydrophilic phosphate portions of the phospholipids are oriented toward the aqueous external or internal environments, while the hydrophobic fatty acid portions face each other within the interior of the membrane itself.
3. Embedded proteins can be hydrophilic, with charged and polar side groups, or hydrophobic, with nonpolar side groups.
4. Small, uncharged polar molecules and small nonpolar molecules, such as N_2, freely pass across the membrane. Hydrophilic substances such as large polar molecules and ions move across the membrane through embedded channel and transport proteins. Water moves across membranes and through channel proteins called aquaporins.

c. Cell walls provide a structural boundary, as well as a permeability barrier for some substances to the internal environments.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Plant cell walls are made of cellulose and are external to the cell membrane.
2. Other examples are cells walls of prokaryotes and fungi.

Learning Objectives:

LO 2.10 The student is able to use representations and models to pose scientific questions about the properties of cell membranes and selective permeability based on molecular structure. [See **SP 1.4, 3.1**]

LO 2.11 The student is able to construct models that connect the movement of molecules across membranes with membrane structure and function. [See **SP 1.1, 7.1, 7.2**]

Essential knowledge 2.B.2: Growth and dynamic homeostasis are maintained by the constant movement of molecules across membranes.

a. Passive transport does not require the input of metabolic energy; the net movement of molecules is from high concentration to low concentration.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Passive transport plays a primary role in the import of resources and the export of wastes.
2. Membrane proteins play a role in facilitated diffusion of charged and polar molecules through a membrane.

To foster student understanding of this concept, instructors can choose an illustrative example such as:

- Glucose transport
- Na^+/K^+ transport

✘ *There is no particular membrane protein that is required for teaching this concept.*

3. External environments can be hypotonic, hypertonic or isotonic to internal environments of cells.

b. Active transport requires free energy to move molecules from regions of low concentration to regions of high concentration.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Active transport is a process where free energy (often provided by ATP) is used by proteins embedded in the membrane to "move" molecules and/or ions across the membrane and to establish and maintain concentration gradients.
2. Membrane proteins are necessary for active transport.

c. The processes of endocytosis and exocytosis move large molecules from the external environment to the internal environment and vice versa, respectively.

Evidence of student learning is a demonstrated understanding of each of the following:

1. In exocytosis, internal vesicles fuse with the plasma membrane to secrete large macromolecules out of the cell.
2. In endocytosis, the cell takes in macromolecules and particulate matter by forming new vesicles derived from the plasma membrane.

Learning Objective:

LO 2.12 The student is able to use representations and models to analyze situations or solve problems qualitatively and quantitatively to investigate whether dynamic homeostasis is maintained by the active movement of molecules across membranes. [See **SP 1.4**]

Essential knowledge 2.B.3: Eukaryotic cells maintain internal membranes that partition the cell into specialized regions.

a. Internal membranes facilitate cellular processes by minimizing competing interactions and by increasing surface area where reactions can occur.

b. Membranes and membrane-bound organelles in eukaryotic cells localize (compartmentalize) intracellular metabolic processes and specific enzymatic reactions. [See also **4.A.2**]

4. RNA viruses lack replication error-checking mechanisms, and thus have higher rates of mutation.
5. Related viruses can combine/recombine information if they infect the same host cell.
6. HIV is a well-studied system where the rapid evolution of a virus within the host contributes to the pathogenicity of viral infection.

b. The reproductive cycles of viruses facilitate transfer of genetic information.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Viruses transmit DNA or RNA when they infect a host cell. [See also **1.B.3**]

   To foster student understanding of this concept, instructors can choose an illustrative example such as:

   - Transduction in bacteria
   - Transposons present in incoming DNA

2. Some viruses are able to integrate into the host DNA and establish a latent (lysogenic) infection. These latent viral genomes can result in new properties for the host such as increased pathogenicity in bacteria.

Learning Objectives:

LO 3.29 The student is able to construct an explanation of how viruses introduce genetic variation in host organisms. [See **SP 6.2**]

LO 3.30 The student is able to use representations and appropriate models to describe how viral replication introduces genetic variation in the viral population. [See **SP 1.4**]

Enduring understanding 3.D: Cells communicate by generating, transmitting and receiving chemical signals.

For cells to function in a biological system, they must communicate with other cells and respond to their external environment. Cell-to-cell communication is ubiquitous in biological systems, from archaea and bacteria to multicellular organisms. The basic chemical processes by which cells communicate are shared across evolutionary lines of descent, and communication schemes are the products of evolution. Cell-to-cell communication is a component of higher-order biological organization and responses. In multicellular organisms, cell-to-cell and environment-to-cell chemical signaling pathways direct complex processes, ranging from cell and organ differentiation to whole organism physiological responses and behaviors. Certain signal pathways involve direct cell-to-cell contact, operate over very short distances, and may be determined by the structure of the organism or organelle, including plasmodesmata in plants and receptor-to-recognition protein interaction in the vertebrate immune system.

Chemical signals allow cells to communicate without physical contact. The distance between the signal generating cell(s) and the responding cell can be small or large. In this type of signaling pathway, there is often a gradient response, and threshold concentrations are required to trigger the communication pathway.

Chemical signaling pathways in cells are determined by the properties of the molecules involved, the concentrations of signal and receptor molecules, and the binding affinities (fit) between signal and receptor. The signal can be a molecule or a physical or environmental factor. At the cellular level, the receptor is a protein with specificity for the signal molecule; this allows the response pathway to be specific and appropriate. The receptor protein often is the initiation point for a signal cascade that ultimately results in a change in gene expression, protein activity, or physiological state of the cell or organism, including cell death (apoptosis). Defects in any part of the signal pathway often lead to severe or detrimental conditions such as faulty development, metabolic diseases, cancer or death.

Understanding signaling pathways allows humans to modify and manipulate biological systems and physiology. An understanding of the human endocrine system, for example, allowed the development of birth control methods, as well as medicines that control depression, blood pressure and metabolism. Other examples include the ability to control/modify ripening in fruit, agricultural production (growth hormones) and biofilm control.

Essential knowledge 3.D.1: Cell communication processes share common features that reflect a shared evolutionary history.

a. Communication involves transduction of stimulatory or inhibitory signals from other cells, organisms or the environment. [See also **1.B.1**]

b. Correct and appropriate signal transduction processes are generally under strong selective pressure.

c. In single-celled organisms, signal transduction pathways influence how the cell responds to its environment.

   To foster student understanding of this concept, instructors can choose an illustrative example such as:

   - Use of chemical messengers by microbes to communicate with other nearby cells and to regulate specific pathways in response to population density (quorum sensing)
   - Use of pheromones to trigger reproduction and developmental pathways
   - Response to external signals by bacteria that influences cell movement

d. In multicellular organisms, signal transduction pathways coordinate the activities within individual cells that support the function of the organism as a whole.

   To foster student understanding of this concept, instructors can choose an illustrative example such as:

- Epinephrine stimulation of glycogen breakdown in mammals
- Temperature determination of sex in some vertebrate organisms
- DNA repair mechanisms

Learning Objectives:

LO 3.31 The student is able to describe basic chemical processes for cell communication shared across evolutionary lines of descent. [See **SP 7.2**]

LO 3.32 The student is able to generate scientific questions involving cell communication as it relates to the process of evolution. [See **SP 3.1**]

LO 3.33 The student is able to use representation(s) and appropriate models to describe features of a cell signaling pathway. [See **SP 1.4**]

Essential knowledge 3.D.2: Cells communicate with each other through direct contact with other cells or from a distance via chemical signaling.

a. Cells communicate by cell-to-cell contact.

To foster student understanding of this concept, instructors can choose an illustrative example such as:

- Immune cells interact by cell-cell contact, antigen-presenting cells (APCs), helper T-cells and killer T-cells. [See also **2.D.4**]
- Plasmodesmata between plant cells that allow material to be transported from cell to cell.

b. Cells communicate over short distances by using local regulators that target cells in the vicinity of the emitting cell.

To foster student understanding of this concept, instructors can choose an illustrative example such as:

- Neurotransmitters
- Plant immune response
- Quorum sensing in bacteria
- Morphogens in embryonic development

c. Signals released by one cell type can travel long distances to target cells of another cell type.

Evidence of student learning is a demonstrated understanding of the following:

1. Endocrine signals are produced by endocrine cells that release signaling molecules, which are specific and can travel long distances through the blood to reach all parts of the body.

To foster student understanding of this concept, instructors can choose an illustrative example such as:

- Insulin
- Human growth hormone
- Thyroid hormones
- Testosterone
- Estrogen

✘ *No specific system, with the exception of the endocrine system, is required for teaching the concepts in 3.D.2 . Teachers are free to choose a system that best fosters student understanding. Study of the nervous and immune systems is required for concepts detailed in 3.E.2 and 2.D.4.*

Learning Objectives:

LO 3.34 The student is able to construct explanations of cell communication through cell-to-cell direct contact or through chemical signaling. [See **SP 6.2**]

LO 3.35 The student is able to create representation(s) that depict how cell-to-cell communication occurs by direct contact or from a distance through chemical signaling. [See **SP 1.1**]

Essential knowledge 3.D.3: Signal transduction pathways link signal reception with cellular response.

a. Signaling begins with the recognition of a chemical messenger, a ligand, by a receptor protein.

   Evidence of student learning is a demonstrated understanding of each of the following:

   1. Different receptors recognize different chemical messengers, which can be peptides, small chemicals or proteins, in a specific one-to-one relationship.
   2. A receptor protein recognizes signal molecules, causing the receptor protein's shape to change, which initiates transduction of the signal.

      To foster student understanding of this concept, instructors can choose an illustrative example such as:

      - G-protein linked receptors
      - Ligand-gated ion channels
      - Receptor tyrosine kinases

✘ *No particular system is required for teaching the concepts above. Teachers are free to choose a system that best fosters student understanding.*

b. Signal transduction is the process by which a signal is converted to a cellular response.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Signaling cascades relay signals from receptors to cell targets, often amplifying the incoming signals, with the result of appropriate responses by the cell.
2. Second messengers are often essential to the function of the cascade.

   To foster student understanding of this concept, instructors can choose an illustrative example such as:

   - Ligand-gated ion channels
   - Second messengers, such as cyclic GMP, cyclic AMP calcium ions (Ca^{2+}), and inositol triphosphate (IP_3)
3. Many signal transduction pathways include:

   i. Protein modifications (an illustrative example could be how methylation changes the signaling process)

   ii. Phosphorylation cascades in which a series of protein kinases add a phosphate group to the next protein in the cascade sequence

Learning Objectives:

LO 3.36 The student is able to describe a model that expresses the key elements of signal transduction pathways by which a signal is converted to a cellular response. [See **SP 1.5**]

Essential knowledge 3.D.4: Changes in signal transduction pathways can alter cellular response.

a. Conditions where signal transduction is blocked or defective can be deleterious, preventative or prophylactic.

To foster student understanding of this concept, instructors can choose an illustrative example such as:

- Diabetes, heart disease, neurological disease, autoimmune disease, cancer, cholera
- Effects of neurotoxins, poisons, pesticides
- Drugs (Hypertensives, Anesthetics, Antihistamines and Birth Control Drugs)

✘ *Specific mechanisms of these diseases and action of drugs are beyond the scope of the course and the AP Exam.*

Learning Objectives:

LO 3.37 The student is able to justify claims based on scientific evidence that changes in signal transduction pathways can alter cellular response. [See **SP 6.1**]

LO 3.38 The student is able to describe a model that expresses key elements to show how change in signal transduction can alter cellular response. [See **SP 1.5**]

LO 3.39 The student is able to construct an explanation of how certain drugs affect signal reception and, consequently, signal transduction pathways. [See **SP 6.2**]

Enduring understanding 3.E: Transmission of information results in changes within and between biological systems.

Evolution operates on genetic information that is passed to subsequent generations. However, transmission of nonheritable information also determines critical roles that influence behavior within and between cells, organisms and populations. These responses are dependent upon or influenced by underlying genetic information, and decoding in many cases is complex and affected by external conditions. For example, biological rhythms, mating behaviors, flowering, animal communications and social structures are dependent on and elicited by external signals and may encompass a range of responses and behaviors.

Organ systems have evolved that sense and process external information to facilitate and enhance survival, growth and reproduction in multicellular organisms. These include sensory systems that monitor and detect physical and chemical signals from the environment and other individuals in the population and that influence an animal's well-being. The nervous system interacts with sensory and internal body systems to coordinate responses and behaviors, ranging from movement to metabolism to respiration. Loss of function and coordination within the nervous system often results in severe consequences, including changes in behavior, loss of body functions and even death.

Knowledge and understanding of the structures and functions of the nervous system are needed to understand this coordination. The features of an animal's nervous system are evolutionarily conserved, with the basic cellular structure of neurons the same across species. The physiological and cellular processes for signal formation and propagation involve specialized membrane proteins, signaling molecules and ATP. Neurological signals can operate and coordinate responses across significant distances within an organism. The brain serves as a master neurological center for processing information and directing responses, and different regions of the brain serve different functions. Structures and associated functions for animal brains are products of evolution, and increasing complexity follows evolutionary lines.

Populations of organisms exist in communities. Individual behavior influences population behavior, and both are the products of information recognition, processing and transmission. Communication among individuals within a population may increase the long-term success of

Big Idea 4: Biological systems interact, and these systems and their interactions possess complex properties.

All biological systems are composed of parts that interact with each other. These interactions result in characteristics not found in the individual parts alone. In other words, "the whole is greater than the sum of its parts." All biological systems from the molecular level to the ecosystem level exhibit properties of biocomplexity and diversity. Together, these two properties provide robustness to biological systems, enabling greater resiliency and flexibility to tolerate and respond to changes in the environment. Biological systems with greater complexity and diversity often exhibit an increased capacity to respond to changes in the environment.

At the molecular level, the subcomponents of a biological polymer determine the properties of that polymer. At the cellular level, organelles interact with each other as part of a coordinated system that keeps the cell alive, growing and reproducing. The repertory of subcellular organelles and biochemical pathways reflects cell structure and differentiation. Additionally, interactions between external stimuli and gene expression result in specialization and divergence of cells, organs and tissues. Interactions and coordination between organs and organ systems determine essential biological activities for the organism as a whole. External and internal environmental factors can trigger responses in individual organs that, in turn, affect the entire organism. At the population level, as environmental conditions change, community structure changes both physically and biologically. The study of ecosystems seeks to understand the manner in which species are distributed in nature and how they are influenced by their abiotic and biotic interactions, e.g., species interactions. Interactions between living organisms and their environments result in the movement of matter and energy.

Interactions, including competition and cooperation, play important roles in the activities of biological systems. Interactions between molecules affect their structure and function. Competition between cells may occur under conditions of resource limitation. Cooperation between cells can improve efficiency and convert sharing of resources into a net gain in fitness for the organism. Coordination of organs and organ systems provides an organism with the ability to use matter and energy effectively.

Variations in components within biological systems provide a greater flexibility to respond to changes in its environment. Variation in molecular units provides cells with a wider range of potential functions. A population is often measured in terms of genomic diversity and its ability to respond to change. Species with genetic variation and the resultant phenotypes can respond and adapt to changing environmental conditions.

Enduring understanding 4.A: Interactions within biological systems lead to complex properties.

All biological systems, from cells to ecosystems, are composed of parts that interact with each other. When this happens, the resulting interactions enable characteristics not found in the individual parts alone. In other words, "the whole is greater than the sum of its parts," a phenomenon sometimes referred to as "emergent properties."

At the molecular level, the properties of a polymer are determined by its subcomponents and their interactions. For example, a DNA molecule is comprised of a series of nucleotides that can be linked together in various sequences; the resulting polymer carries hereditary material for the cell, including information that controls cellular activities. Other polymers important to life include carbohydrates, lipids and proteins. The interactions between the constituent parts of polymers, their order, their molecular orientation and their interactions with their environment define the structure and function of the polymer.

At the cellular level, organelles interact with each other and their environment as part of a coordinated system that allows cells to live, grow and reproduce. For example, chloroplasts produce trioses through the process of photosynthesis; however, once trioses are synthesized and exported from the chloroplast, they may be packaged by the Golgi body and distributed to the edge of the cell where they serve as a building block for cellulose fibers comprising the cell wall. Similarly, several organelles are involved in the manufacture and export of protein. The repertory of subcellular organelles determines cell structure and differentiation; for instance, the components of plant leaf cells are different from the components of plant root cells, and the components of human liver cells are different from those in the retina. Thus, myriad interactions of different parts at the subcellular level determine the functioning of the entire cell, which would not happen with the activities of individual organelles alone.

In development, interactions between regulated gene expression and external stimuli, such as temperature or nutrient levels or signal molecules, result in specialization of cells, organs and tissues. Differentiation of the germ layers during vertebrate gastrulation is an example of one such divergence. The progression of stem cells to terminal cells can also be explained by the interaction of stimuli and genes. Additionally, cells, organs and tissues may change due to changes in gene expression triggered by internal cues, including regulatory proteins and growth factors, which result in the structural and functional divergence of cells.

Organisms exhibit complex properties due to interactions of their constituent parts, and interactions and coordination between organs and organ systems provide essential biological activities for the organism as a whole. Examples include the vessels and hearts of animals and the roots and shoots of plants. Environmental factors such as temperature can trigger responses in individual organs that, in turn, affect the entire organism.

Interactions between populations within communities also lead to complex properties. As environmental conditions change in time and space, the structure of the community changes both physically and biologically, resulting in a mosaic in the landscape (variety or patterns) in a community. Communities are comprised of different populations of organisms that interact with each other in either negative or positive ways (e.g., competition, parasitism and mutualism); community ecology seeks to understand the manner in which groupings of species are distributed in nature, and how they are influenced by their abiotic environment and species interactions. The physical structure of a community is affected by abiotic factors, such as the depth and flow of water in a stream, and also by the spatial distribution of organisms, such as in the canopy of trees. The mix of species in terms of both the number of individuals and the diversity of species defines the structure of the community. Mathematical or computer models can be used to illustrate and investigate interactions of populations within a community and the effects of environmental impacts on a community. Community change resulting from disturbances sometimes follows a pattern (e.g., succession following a wildfire), and in other cases is random and unpredictable (e.g., founder effect).

At the ecosystem level, interactions among living organisms and with their environment result in the movement of matter and energy. Ecosystems include producers, consumers, decomposers and a pool of organic matter, plus the physiochemical environment that provides the living conditions for the biotic components. Matter, but not energy, can be recycled within an ecosystem via biogeochemical cycles. Energy flows through the system and can be converted from one type to another, e.g., energy available in sunlight is converted to chemical bond energy via photosynthesis. Understanding individual organisms in relation to the environment and the diverse interactions that populations have with one another (e.g., food chains and webs) informs the development of ecosystem models; models allow us to identify the impact of changes in biotic and abiotic factors. Human activities affect ecosystems on local, regional and global scales.

Essential knowledge 4.A.1: The subcomponents of biological molecules and their sequence determine the properties of that molecule.

a. Structure and function of polymers are derived from the way their monomers are assembled.

   Evidence of student learning is a demonstrated understanding of each of the following:

   1. In nucleic acids, biological information is encoded in sequences of nucleotide monomers. Each nucleotide has structural components: a five-carbon sugar (deoxyribose or ribose), a phosphate and a nitrogen base (adenine, thymine, guanine, cytosine or uracil). DNA and RNA differ in function and differ slightly in structure, and these structural differences account for the differing functions. [See also **1.D.1, 2.A.3, 3.A.1**]

   ✘ *The molecular structure of specific nucleotides is beyond the scope of the course and the AP Exam.*

   2. In proteins, the specific order of amino acids in a polypeptide (primary structure) interacts with the environment to determine the overall shape of the protein, which also involves secondary tertiary and quaternary structure and, thus, its function. The R group of an amino acid can be categorized by chemical properties (hydrophobic, hydrophilic and ionic), and the interactions

of these R groups determine structure and function of that region of the protein. [See also **1.D.1, 2.A.3, 2.B.1**]

✘ *The molecular structure of specific amino acids is beyond the scope of the course and the AP Exam.*

3. In general, lipids are nonpolar; however, phospholipids exhibit structural properties, with polar regions that interact with other polar molecules such as water, and with nonpolar regions where differences in saturation determine the structure and function of lipids. [See also **1.D.1, 2.A.3, 2. B.1**]

✘ *The molecular structure of specific lipids is beyond the scope of the course and the AP Exam.*

4. Carbohydrates are composed of sugar monomers whose structures and bonding with each other by dehydration synthesis determine the properties and functions of the molecules. Illustrative examples include: cellulose versus starch.

✘ *The molecular structure of specific carbohydrate polymers is beyond the scope of the course and the AP Exam.*

b. Directionality influences structure and function of the polymer.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Nucleic acids have ends, defined by the 3' and 5' carbons of the sugar in the nucleotide, that determine the direction in which complementary nucleotides are added during DNA synthesis and the direction in which transcription occurs (from 5' to 3'). [See also **3.A.1**]

2. Proteins have an amino (NH_2) end and a carboxyl (COOH) end, and consist of a linear sequence of amino acids connected by the formation of peptide bonds by dehydration synthesis between the amino and carboxyl groups of adjacent monomers.

3. The nature of the bonding between carbohydrate subunits determines their relative orientation in the carbohydrate, which then determines the secondary structure of the carbohydrate.

Learning Objectives:

LO 4.1 The student is able to explain the connection between the sequence and the subcomponents of a biological polymer and its properties. [See **SP 7.1**]

LO 4.2 The student is able to refine representations and models to explain how the subcomponents of a biological polymer and their sequence determine the properties of that polymer. [See **SP 1.3**]

LO 4.3 The student is able to use models to predict and justify that changes in the subcomponents of a biological polymer affect the functionality of the molecule. [See **SP 6.1, 6.4**]

Essential knowledge 4.A.2: The structure and function of subcellular components, and their interactions, provide essential cellular processes.

a. Ribosomes are small, universal structures comprised of two interacting parts: ribosomal RNA and protein. In a sequential manner, these cellular components interact to become the site of protein synthesis where the translation of the genetic instructions yields specific polypeptides. [See also **2.B.3**]

b. Endoplasmic reticulum (ER) occurs in two forms: smooth and rough. [See also **2.B.3**]

   Evidence of student learning is a demonstrated understanding of each of the following:

   1. Rough endoplasmic reticulum functions to compartmentalize the cell, serves as mechanical support, provides site-specific protein synthesis with membrane-bound ribosomes and plays a role in intracellular transport.

   2. In most cases, smooth ER synthesizes lipids.

   ✘ *Specific functions of smooth ER in specialized cells are beyond the scope of the course and the AP Exam.*

c. The Golgi complex is a membrane-bound structure that consists of a series of flattened membrane sacs (cisternae). [See also **2.B.3**]

   Evidence of student learning is a demonstrated understanding of the following:

   1. Functions of the Golgi include synthesis and packaging of materials (small molecules) for transport (in vesicles), and production of lysosomes.

   ✘ *The role of this organelle in specific phospholipid synthesis and the packaging of enzymatic contents of lysosomes, peroxisomes and secretory vesicles are beyond the scope of the course and the AP Exam.*

d. Mitochondria specialize in energy capture and transformation. [See also **2.A.2**, **2.B.3**]

   Evidence of student learning is a demonstrated understanding of each of the following:

   1. Mitochondria have a double membrane that allows compartmentalization within the mitochondria and is important to its function.

   2. The outer membrane is smooth, but the inner membrane is highly convoluted, forming folds called cristae.

   3. Cristae contain enzymes important to ATP production; cristae also increase the surface area for ATP production.

e. Lysosomes are membrane-enclosed sacs that contain hydrolytic enzymes, which are important in intracellular digestion, the recycling of a cell's organic materials and programmed cell death (apoptosis). Lysosomes carry out intracellular digestion in a variety of ways. [See also **2.B.3**]

✘ *Specific examples of how lysosomes carry out intracellular digestion are beyond the scope of the course and the AP Exam.*

f. A vacuole is a membrane-bound sac that plays roles in intracellular digestion and the release of cellular waste products. In plants, a large vacuole serves many functions, from storage of pigments or poisonous substances to a role in cell growth. In addition, a large central vacuole allows for a large surface area to volume ratio. [See also **2. A.3, 2.B.3**]

g. Chloroplasts are specialized organelles found in algae and higher plants that capture energy through photosynthesis. [See also **2.A.2, 2 B.3**]

Evidence of student learning is a demonstrated understanding of each of the following:

1. The structure and function relationship in the chloroplast allows cells to capture the energy available in sunlight and convert it to chemical bond energy via photosynthesis.

2. Chloroplasts contain chlorophylls, which are responsible for the green color of a plant and are the key light-trapping molecules in photosynthesis. There are several types of chlorophyll, but the predominant form in plants is chlorophyll *a*.

✘ *The molecular structure of chlorophyll* a *is beyond the scope of the course and the AP Exam.*

3. Chloroplasts have a double outer membrane that creates a compartmentalized structure, which supports its function. Within the chloroplasts are membrane-bound structures called thylakoids. Energy-capturing reactions housed in the thylakoids are organized in stacks, called "grana," to produce ATP and $NADPH_2$, which fuel carbon-fixing reactions in the Calvin-Benson cycle. Carbon fixation occurs in the stroma, where molecules of CO_2 are converted to carbohydrates.

Learning Objectives:

LO 4.4 The student is able to make a prediction about the interactions of subcellular organelles. [See **SP 6.4**]

LO 4.5 The student is able to construct explanations based on scientific evidence as to how interactions of subcellular structures provide essential functions. [See **SP 6.2**]

LO 4.6 The student is able to use representations and models to analyze situations qualitatively to describe how interactions of subcellular structures, which possess specialized functions, provide essential functions. [See **SP 1.4**]

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Learning Objectives:

LO 4.14 The student is able to apply mathematical routines to quantities that describe interactions among living systems and their environment, which result in the movement of matter and energy. [See **SP 2.2**]

LO 4.15 The student is able to use visual representations to analyze situations or solve problems qualitatively to illustrate how interactions among living systems and with their environment result in the movement of matter and energy. [See **SP 1.4**]

LO 4.16 The student is able to predict the effects of a change of matter or energy availability on communities.[See **SP 6.4**]

Enduring understanding 4.B: Competition and cooperation are important aspects of biological systems.

Competition and cooperation play important roles in the activities of biological systems at all levels of organization. Living systems require a myriad of chemical reactions on a constant basis, and each of these chemical reactions relies on the cooperation between a particular enzyme and specific substrates, coenzymes and cofactors. Chemical inhibitors may compete for the active sites of enzymes that, in turn, affect the ability of the enzyme to catalyze its chemical reactions. Thus, interactions between molecules affect their structure and function. Other examples of this phenomenon include receptor-ligand interactions and changes in protein structure due to amino acid sequence.

Similar cells may compete with each other when resources are limited; for example, organisms produce many more spores or seeds than will germinate. Competition for resources also determines which organisms are successful and produce offspring. In the vertebrate immune system, competition via antigen-binding sites determines which B-cell lineages are stimulated to reproduce.

The cooperation of parts extends to the organism that depends on the coordination of organs and organ systems, such as between the digestive and excretory systems of an animal or the roots and shoots of a plant. Cooperation within organisms increases efficiency in the use of matter and energy. For example, without the coordination and cooperation of its shoot and roots, a plant would be unable to survive if its root system was too small to absorb water to replace the water lost through transpiration by the shoot. Similarly, exchange of oxygen and carbon dioxide in an animal depends on the functioning of the respiratory and circulatory systems. Furthermore, population interactions influence patterns of species distribution and abundance, and global distribution of ecosystems changes substantially over time.

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**]

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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.

environment. Keystone species, predators, and essential abiotic and biotic factors contribute to maintaining the diversity of an ecosystem. For example, the removal of sea otters or mollusks can drastically affect a marine ecosystem, and the introduction of an exotic plant or animal species can likewise affect the stability of a terrestrial ecosystem.

Essential knowledge 4.C.1: Variation in molecular units provides cells with a wider range of functions.

a. Variations within molecular classes provide cells and organisms with a wider range of functions. [See also **2.B.1**, **3.A.1**, **4.A.1**, **4.A.2**]

   To foster student understanding of this concept, instructors can choose an illustrative example such as:

   - Different types of phospholipids in cell membranes
   - Different types of hemoglobin
   - MHC proteins
   - Chlorophylls
   - Molecular diversity of antibodies in response to an antigen

b. Multiple copies of alleles or genes (gene duplication) may provide new phenotypes. [See also **3.A.4**, **3.C.1**]

   Evidence of student learning is a demonstrated understanding of each of the following:

   1. A heterozygote may be a more advantageous genotype than a homozygote under particular conditions, since with two different alleles, the organism has two forms of proteins that may provide functional resilience in response to environmental stresses.
   2. Gene duplication creates a situation in which one copy of the gene maintains its original function, while the duplicate may evolve a new function.

      To foster student understanding of this concept, instructors can choose an illustrative example such as:

      - The antifreeze gene in fish

Learning Objective:

LO 4.22 The student is able to construct explanations based on evidence of how variation in molecular units provides cells with a wider range of functions. [See **SP 6.2**]

Essential knowledge 4.C.2: Environmental factors influence the expression of the genotype in an organism.

a. Environmental factors influence many traits both directly and indirectly. [See also **3.B.2**, **3.C.1**]