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**]