Biology and Biochemistry

Outline

I. Introduction, Percentages, and Percentiles

The Biological and Biochemical Foundations of Living Systems section asks you to solve problems by combining your knowledge of biological and biochemical concepts with your scientific inquiry and reasoning skills. This section tests processes that are unique to living organisms, such as growing and reproducing, maintaining a constant internal environment, acquiring materials and energy, sensing and responding to environmental changes, and adapting. It also tests how cells and organ systems within an organism act independently and in concert to accomplish these processes, and it asks you to reason about these processes at various levels of biological organization within a living system.

This section is designed to:

1. Test introductory-level biology, organic chemistry, and inorganic chemistry concepts.
2. Test biochemistry concepts at the level taught in many colleges and universities in first-semester biochemistry courses.
3. Test cellular and molecular biology topics at the level taught in many colleges and universities in introductory biology sequences and first-semester biochemistry courses.
4. Test basic research methods and statistics concepts described by many baccalaureate faculty as important to success in introductory science courses.
5. Require you to demonstrate your scientific inquiry and reasoning, research methods, and statistics skills as applied to the natural sciences.

59 Questions, 95 minutes:

1. 10 Passage-based sets of questions with 4-6 questions per set
2. 15 Discrete questions

The questions that you see in this section of the MCAT exam are likely to be distributed in the ways described below. These are the approximate percentages of questions you'll see on a test for each discipline, foundational concept, and scientific inquiry and reasoning skill.

Discipline	Foundational Concept	Scientific Inquiry and Reasoning Skill
First semester biochemistry, 25%	FC 1, 55%	Skill 1, 35%
Introduction biology, 65%	FC 2, 20%	Skill 2, 45%
General biology, 5%	FC 3, 25%	Skill 3, 10%
Organic chemistry, 5%		Skill 4, 10%

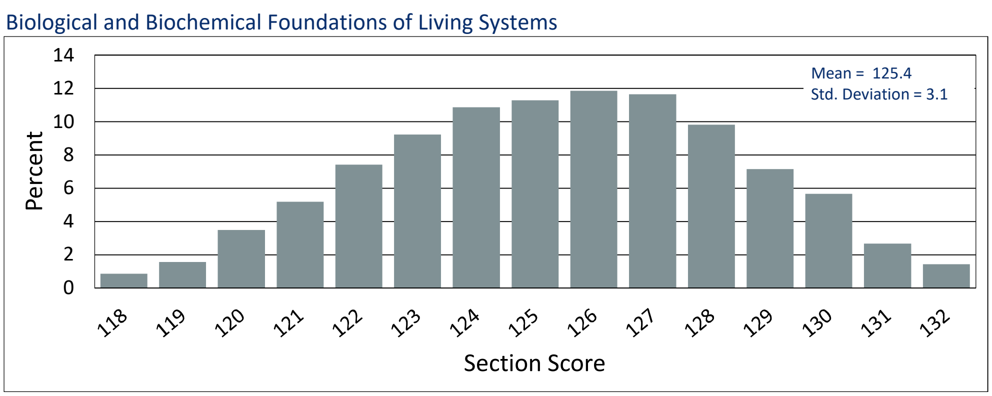
Table 1 Question distribution based on discipline, foundational concept, and scientific inquiry and reasoning skill

Subject	Bio-BCHM Section (%)	CP Section (%)	Average (%)
Biochemistry	25	25	25
Biology	65	5	35
General Chemistry	5	30	17.5
Physics	0	25	12.5
Organic Chemistry	5	15	10

Table 2 Subject percentage by section

Section	Foundational Concept	Percentage (%)
Bio-BCHM	1	55
	2	20
	3	25
CP	4	40
	5	60

Table 3 Foundational concept percentage by section



Section Score	Percentile Rank
118	1
119	2
120	6
121	11
122	18
123	28
124	39
125	50
126	62
127	73
128	83
129	90
130	96
131	99
132	100

Figure 1 and **Table 4** CP section score percent and percentile rank

II. Foundational Concept 1 - Biochemistry

Biomolecules have unique properties that determine how they contribute to the structure and function of cells and how they participate in the processes necessary to maintain life. The unique chemical and structural properties of biomolecules determine the roles they play in cells. The proper functioning of a living system depends on the many components acting harmoniously in response to a constantly changing environment. Biomolecules are constantly formed or degraded in response to the perceived needs of the organism.

A. Protein Structure and Function

Category 1A focuses on the structural and functional complexity of proteins arising from their component amino acids, the sequence in which the amino acids are covalently bonded, and the three-dimensional structures the proteins adopt in an aqueous environment. Proteins are macromolecules formed from amino acids that adopt well-defined, 3D structures with chemical properties that are responsible for their participation in virtually every process occurring within and between cells. The 3D structure of proteins is a direct consequence of the nature of the covalently-bonded sequence of amino acids, their chemical and physical properties, and the way in which the whole assembly interacts with water.

Enzymes are proteins that interact in highly regiospecific and stereospecific ways with dissolved solutes. They either facilitate the chemical transformation of these solutes, or allow for their transport innocuously. Dissolved solutes compete for protein-binding sites, and protein conformational dynamics give rise to mechanisms capable of controlling enzymatic activity. The infinite variability of potential amino acid sequences allows for adaptable responses to pathogenic organisms and materials. The rigidity of some amino acid sequences makes them suitable for structural roles in complex living systems.

Content in this category covers a range of protein behaviors which originate from the unique chemistry of amino acids themselves. Amino acid classifications and protein structural elements are covered. Special emphasis is placed on enzyme catalysis, including mechanistic considerations, kinetics, models of enzyme-substrate interaction, and regulation. The topics and subtopics in this category are the following:

1. Amino Acids
    a. Physical properties - absolute configuration at the α-carbon; dipolar ions (zwitterions); classification as acidic-basic and hydrophobic-hydrophilic
    b. Amino-acid reactions - sulfur linkage for cysteine and cystine; peptide linkage in peptides, polypeptides, and proteins; peptide-bond hydrolysis

2. Protein Structure
    a. Levels of structure - primary through quaternary structure; tertiary structure (role of proline, cystine, hydrophobic bonding)
    b. Conformational stability - folding and denaturing; hydrophobic interactions; solvation layer and entropy
    c. Separation techniques - isoelectric point and electrophoresis

3. Non-Enzymatic Protein Function
    a. Binding
    b. Immune system
    c. Motor proteins

4. Enzymatic Structure and Function
    a. Functions of enzymes in catalyzing biological reactions
    b. Enzyme classification by reaction type
    c. Reduction of activation energy
    d. Substrates and enzyme specificity
    e. Active site model and induced fit model
    f. Mechanisms of catalysis - cofactors, coenzymes, water-soluble vitamins
    g. Effects of local conditions on enzyme activity

5. Control of Enzyme Activity
    a. Kinetics - catalysis, Michaelis-Menten kinetics, cooperativity
    b. Feedback regulation
    c. Inhibition types - competitive, non-competitive, mixed, uncompetitive
    d. Regulator enzymes - allosteric enzymes, covalently-modified enzymes, zymogens

B. Transmission of Genetic Information

Category 1B focuses on the molecular mechanisms responsible for the transfer of sequence-specific genetic information between biopolymers which ultimately results in the synthesis of proteins—gene to protein. Biomolecules and biomolecular assemblies interact in specific, highly-regulated ways to transfer sequence information between biopolymers in living organisms. By storing and transferring biological information, DNA and RNA enable living organisms to reproduce their complex components from one generation to the next. The nucleotide monomers of these biopolymers, being joined by phosphodiester linkages, form a polynucleotide molecule with a “backbone” composed of repeating sugar-phosphate units and “appendages” of nitrogenous bases. The unique sequence of bases in each gene provides specific information to the cell.

DNA molecules are composed of two polynucleotides that spiral around an imaginary axis, forming a double helix. The two polynucleotides are held together by hydrogen bonds between the paired bases and van der Waals interactions between the stacked bases. The pairing between the bases of two polynucleotides is very specific, and its complementarity allows for a precise replication of the DNA molecule. The DNA inherited by an organism leads to specific traits by dictating the synthesis of the biomolecules (RNA molecules and proteins) involved in protein synthesis. While every cell in a multicellular organism inherits the same DNA, its expression is precisely regulated such that different genes are expressed by cells at different stages of development, by cells in different tissues, and by cells exposed to different stimuli.

The topics included in this category concern not only the molecular mechanisms of the transmission of genetic information from the gene to the protein (transcription and translation), but also the biosynthesis of the important molecules and molecular assemblies that are involved in these mechanisms. The control of gene expression in prokaryotes and eukaryotes is also included.

Broadly speaking, the field of biotechnology uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use. The biotechnological techniques emphasized in this category, however, are those that take advantage of the complementary structure of double-stranded DNA molecules to synthesize, sequence, and amplify them, and to analyze and identify unknown polynucleotide sequences. Included within this treatment of biotechnology are those practical applications which directly impact humans, such as medical applications, human gene therapy, and pharmaceuticals.

Content in this category covers the biopolymers, including ribonucleic acid (RNA), deoxyribonucleic acid (DNA), proteins, and the biochemical processes involved in carrying out the transfer of biological information from DNA. The topics and subtopics in this category are the following:

1. Nucleic Acid Structure and Function
    a. Nucleotides and nucleosides - sugar phosphate backbone; pyrimidine and purine residues
    b. DNA - double helix and Watson-Crick model of DNA structure
    c. Base pairing specificity - AT, GC, AU
    d. Function in transmission of genetic information
    e. DNA denaturation, re-annealing, hybridization

2. DNA Replication and Repair
    a. Mechanism of replication - separation of strands and specific coupling of free nucleic acids
    b. Semi-conservative nature of replication
    c. Specific enzymes involved in replication
    d. Origins of replication - one origin in bacteria, multiple origins in eukaryotes
    e. Replicating the 3' ends of DNA molecules - telomerase
    f. Repair during replication
    g. Repair of mutations

3. Genetic Code
    a. Central dogma: DNA to RNA to protein
    b. Messenger RNA (mRNA) and transfer RNA (tRNA)
    c. Triplet mRNA code and the tRNA codon-anticodon relationship
    d. Degenerate code - wobble pairing in tRNA
    e. Missense and nonsense codons
    f. Initiation and termination codons

4. Transcription
    a. tRNA and ribosomal RNA (rRNA)
    b. Mechanism of transcription
    c. mRNA processing in eukaryotes - intron splicing and exons
    d. Ribozymes, spliceosomes, small nuclear ribonucleoproteins (snRNP), small nuclear RNA (snRNA)
    e. Functional and evolutionary importance of introns

5. Translation
    a. Roles of mRNA, tRNA, rRNA
    b. Role and structure of ribosomes
    c. Initiation, termination, cofactors
    d. Post-translational modification of proteins

6. Eukaryotic Chromosome Organization
    a. Chromosomal proteins
    b. Single copy vs. repetitive DNA
    c. Supercoiling
    d. Heterochromatin vs. euchromatin
    e. Telomeres and centromeres

7. Control of Gene Expression in Prokaryotes
    a. Operon concept - Jacob-Monod model
    b. Gene repression in bacteria
    c. Positive control in bacteria

8. Control of Gene Expression in Eukaryotes
    a. Transcription regulation
    b. DNA binding proteins and transcription factors
    c. Gene amplification and duplication
    d. Post-transcriptional control - intron splicing and exons
    e. Cancer as a failure of normal cellular controls, oncogenes, tumor suppressor genes
    f. Regulation of chromatin structure and DNA methylation
    g. Role of non-coding RNA

9. Recombinant DNA and Biotechnology
    a. Gene cloning, restriction enzymes, and expressing cloned genes
    b. DNA libraries
    c. Generation of cDNA
    d. Hybridization
    e. Polymerase chain reaction (PCR)
    f. Gel electrophoresis and Southern blotting
    g. DNA sequencing
    h. Analyzing gene expression
    i. Determining gene function
    j. Stem cells
    k. Practical applications of DNA technology - medical applications, human gene therapy, pharmaceuticals, forensic evidence, environmental cleanup, agriculture
    l. Safety and ethics of DNA technology

C. Transmission of Heritable Information

Category 1C focuses on the mechanisms that function to transmit the heritable information stored in DNA from generation to generation and the processes that increase genetic diversity. The information necessary to direct life functions is contained within discrete nucleotide sequences transmitted from generation to generation by mechanisms that, by nature of their various processes, provide the raw materials for evolution by increasing genetic diversity. Specific sequences of deoxyribonucleic acids store and transfer the heritable information necessary for the continuation of life from one generation to the next. These sequences, called genes — being part of longer DNA molecules — are organized, along with various proteins, into biomolecular assemblies called chromosomes.

Chromosomes pass from parents to offspring in sexually-reproducing organisms. The processes of meiosis and fertilization maintain a species' chromosome count during the sexual life cycle. Because parents pass on discrete heritable units that retain their separate identities in offspring, the laws of probability can be used to predict the outcome of some, but not all, genetic crosses. The behavior of chromosomes during meiosis and fertilization is responsible for most of the genetic variation that arises each generation. Mechanisms that contribute to this genetic variation include independent assortment of chromosomes, crossing over, and random fertilization. Other mechanisms, such as mutation, random genetic drift, bottlenecks, and immigration, exist with the potential to affect the genetic diversity of individuals and populations. Collectively, the genetic diversity that results from these processes provides the raw material for evolution by natural selection.

The content in this category covers the mechanisms by which heritable information is transmitted from generation to generation, and the evolutionary processes that generate and act upon genetic variation. The topics and subtopics in this category are the following:

1. Mendelian Concepts
    a. Phenotype and genotype
    b. Gene and locus
    c. Allele - single and multiple
    d. Homozygosity and heterozygosity
    e. Wild-type
    f. Recessiveness, complete dominance, co-dominance
    g. Incomplete dominance, leakage, penetrance, and expressivity
    h. Hybridization - viability
    i. Gene pool

2. Meiosis and Other Factors Affecting Genetic Variability
    a. Significance of meiosis
    b. Important differences between meiosis and mitosis
    c. Segregation of genes - independent assortment; recombination (single and double crossovers, synaptonemal complex, tetrad); sex-linked characteristics; very few genes on Y chromosome; sex determination, cytoplasmic/extranuclear inheritance
    d. Mutation - general concept of mutation (error in DNA sequence); types of mutations (random, translation error, transcription error, base substitution, inversion, addition, selection, translocation, mispairing); advantageous vs. deleterious mutation; inborn errors of metabolism; relationship between mutagens to carcinogens
    e. Genetic drift
    f. Synapsis or crossing-over mechanism for increasing genetic diversity

3. Analytic Methods
    a. Hardy-Weinberg principle
    b. Testcross - backcross and concepts of parental, F1, and F2 generations
    c. Gene mapping - crossover frequencies
    d. Biometry - statistical methods

4. Evolution
    a. Natural selection - fitness; selection by differential reproduction; natural and group selection; evolutionary success as increase in percent representation in the gene pool of the next generation
    b. Speciation - polymorphism; adaptation and specialization; inbreeding, outbreeding, and bottlenecks
    c. Evolutionary time as measured by gradual random changes in genome

D. Principles of Bioenergetics and Fuel Metabolism

Category 1D focuses on the biomolecules and regulated pathways involved in harvesting chemical energy stored in fuel molecules, which serves as the driving force for all of the processes that take place within a living system. Living things harness energy from fuel molecules in a controlled manner in order to sustain all of the processes responsible for maintaining life. Cell maintenance and growth is energetically costly. Cells harness the energy stored in fuel molecules, such as carbohydrates and fatty acids, and convert it into smaller units of chemical potential known as adenosine triphosphate (ATP). The hydrolysis of ATP provides a ready source of energy for cells that can be coupled to other chemical processes in order to make them thermodynamically favorable. Fuel molecule mobilization, transport, and storage are regulated according to the needs of the organism.

The content in this category covers the principles of bioenergetics and fuel molecule catabolism. Details of oxidative phosphorylation including the role of chemiosmotic coupling and biological electron transfer reactions are covered, as are the general features of fatty acid and glucose metabolism. Additionally, regulation of these metabolic pathways, fuel molecule mobilization, transport, and storage are covered. The topics and subtopics in this category are the following:

1. Principles of Bioenergetics
    a. Bioenergetics and thermodynamics - standard free energy $\Delta G°$ and the equilibrium constant K_{eq}; Le Châtelier's principle; endothermic and exothermic reactions; free energy ΔG and spontaneous reactions
    b. Phosphoryl group transfers, ATP, and ATP hydrolysis
    c. Biological oxidation-reduction reactions - half-reactions, soluble electron carriers, and flavoproteins

2. Carbohydrates
    a. Nomenclature, common names, and classification
    b. Absolute configuration, epimers, and anomers
    c. Cyclic sugars and conformations of hexoses
    d. Hydrolysis of the glycosidic linkage
    e. Monosaccharides, disaccharides, and polysaccharides

3. Glycolysis, Gluconeogenesis, and the Pentose Phosphate Pathway
    a. Glycolysis - substrates, products, feeder pathways, and anaerobic fermentation
    b. Gluconeogenesis
    c. Pentose phosphate pathway
    d. Net molecular and energetic results of aerobic respiration

4. Principles of Metabolic Regulation
    a. Regulation of metabolic pathways - maintenance of a dynamic stead state
    b. Regulation of glycolysis and gluconeogenesis
    c. Regulation of glycogen metabolism - allosteric and hormonal control
    d. Analysis of metabolic control

5. Citric Acid Cycle
    a. Acetyl-CoA production
    b. Reactions, substrates, products
    c. Regulation
    d. Net molecular and energetic results of respiration process

6. Metabolism of Fatty Acids and Proteins
    a. Physical and chemical properties of fatty acids
    b. Digestion, mobilization, transport of fats
    c. Oxidation of fatty acids - saturated and unsaturated fats
    d. Ketone bodies
    e. Anabolism of fats
    f. Non-template synthesis - biosynthesis of lipids and polysaccharides
    g. Metabolism of proteins

7. Oxidative Phosphorylation
    a. Electron transport chain, substrates, products, and general features of the pathway
    b. Electron transfer in mitochondria - NADH, NADPH, flavoproteins, cytochromes
    c. ATP synthase - chemiosmotic coupling and proton motive force
    d. Net molecular and energetic results of aerobic respiration
    e. Regulation of oxidative phosphorylation
    f. Mitochondria, apoptosis, and oxidative stress

8. Hormonal Regulation and Integration of Metabolism
    a. Higher level integration of hormone structure and function
    b. Tissue specific metabolism
    c. Hormonal regulation of fuel metabolism
    d. Obesity and regulation of body mass

III. Foundational Concept 2 - Cells, Prokaryotes, Viruses

Highly-organized assemblies of molecules, cells, and organs interact to carry out the functions of living organisms. Cells are the basic unit of structure in all living things. Mechanisms of cell division provide not only for the growth and maintenance of organisms but also for the continuation of the species through asexual and sexual reproduction. The unique micro-environment to which a cell is exposed during development and division determines the fate of the cell by impacting gene expression and ultimately the cell's collection and distribution of macromolecules, and its arrangement of subcellular organelles. In multicellular organisms, the processes necessary to maintain life are executed by groups of cells that are organized into specialized structures with specialized functions—both of which result from the unique properties of the cells' component molecules.

A. Levels of Organization

Category 2A focuses on the assemblies of molecules, cells, and groups of cells within single cellular and multicellular organisms that function to execute the processes necessary to maintain life. The processes necessary to maintain life are executed by assemblies of molecules, cells, and groups of cells, all of which are organized into highly-specific structures as determined by the unique properties of their component molecules. The processes necessary to maintain life require that cells create and maintain internal environments within the cytoplasm and within certain organelles 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, as described in the fluid mosaic model, allows the cell to be selectively permeable and dynamic, with homeostasis maintained by the constant movement of molecules across the membranes through a combination of active and passive processes driven by several forces, including electrochemical gradients. Eukaryotic cells also maintain internal membranes that partition the cell into specialized regions. These internal membranes facilitate cellular processes by minimizing conflicting interactions and increasing surface area where chemical reactions can occur. Membrane-bound organelles localize different processes or enzymatic reactions in time and space.

Through interactions between proteins bound to the membranes of adjacent cells, or between membrane- bound proteins and elements of the extracellular matrix, cells of multicellular organisms organize into tissues, organs, and organ systems. Certain membrane-associated proteins also play key roles in providing identification of tissues or recent events in the cell’s history for purposes of recognition of “self” versus foreign molecules.

The content in this category covers the composition, structure, and function of cell membranes; the structure and function of the membrane-bound organelles of eukaryotic cells; and the structure and function of the major cytoskeletal elements. It covers the energetics of and mechanisms by which molecules, or groups of molecules, move across cell membranes. It also covers how cell–cell junctions and the extracellular matrix interact to form tissues with specialized functions. Epithelial tissue and connective tissue are covered in this category. The topics and subtopics in this category are the following:

1. Plasma Membrane
    a. General function in cell containment
    b. Composition of membranes and the fluid mosaic model - phospholipids and phosphatids; sphingolipids and waxes; steroids; proteins
    c. Membrane dynamics
    d. Solute transport across membranes - thermodynamics; osmosis (colligative properties and osmotic pressure); passive transport and membrane channels; active transport (Na-K pump)
    e. Membrane potential
    f. Membrane receptors
    g. Exocytosis and endocytosis
    h. Intracellular junctions - gap junctions, tight junctions, and desmosomes

2. Membrane-Bound Organelles and Defining Characteristics of Eukaryotes
    a. Membrane-bound nucleus, presence of organelles, mitotic division
    b. Nucleus - compartmentalization and storage of genetic information; nucleolus (location and function); nuclear envelope and nuclear pores
    c. Mitochondria - site of ATP production; inner and outer membrane structure; self-replication
    d. Lysosomes - membrane-bound vesicles containing hydrolytic enzymes
    e. Endoplasmic reticulum - rough and smooth components; rough endoplasmic reticulum (site of ribosomes); double membrane structure; role in membrane biosynthesis; role in biosynthesis of secreted proteins
    f. Golgi apparatus - general structure and role in packaging and secretion
    g. Peroxisomes - organelles that collect peroxides

3. Cytoskeleton
    a. General function in cell support and movement
    b. Microfilaments - composition and role in cleavage and contractility
    c. Microtubules - composition and role in support and transport
    d. Intermediate filaments - role in support
    e. Composition and function of cilia and flagella
    f. Centrioles - microtubule organizing centers

4. Tissues Formed from Eukaryotic Cells
    a. Epithelial cells
    b. Connective tissue cells

B. Prokaryotes and Viruses

Category 2B focuses on the structure, growth, physiology, genetics of prokaryotes, and the structure and life cycles of viruses. The highly-organized assembly of molecules that is the cell represents the fundamental unit of structure, function, and organization in all living organisms. In the hierarchy of biological organization, the cell is the simplest collection of matter capable of carrying out the processes that distinguish living organisms. As such, cells have the ability to undergo metabolism; maintain homeostasis, including ionic gradients; the capacity to grow; move in response to their local environments; respond to stimuli; reproduce; and adapt to their environment in successive generations.

Life at cellular levels arises from structural order and its dynamic modulation. It does so in response to signals, thereby reflecting properties that result from individual and interactive features of molecular assemblies, their compartmentalization, and their interaction with environmental signals at many spatial and temporal scales.

The content in this category covers the classification, structure, growth, physiology, and genetics of prokaryotes, and the characteristics that distinguish them from eukaryotes. Viruses are also covered here. The topics and subtopics in this category are the following:

1. Cell Theory
    a. History and development
    b. Impact on biology

2. Classification and Structure of Prokaryotic Cells
    a. Prokaryotic domains - archaea and bacteria
    b. Major classifications of bacteria by shape - bacilli (rod-shaped); spirilli (spiral-shaped); cocci (spherical-shaped)
    c. Lack of nuclear membrane and mitotic apparatus
    d. Lack of typical eukaryotic organelles
    e. Presence of cell wall in bacteria
    f. Flagellar propulsion mechanism

3. Growth and Physiology of Prokaryotic Cells
    a. Reproduction by fission
    b. High degree of genetic adaptability and acquisition of antibiotic resistance
    c. Exponential growth
    d. Existence of anaerobic and aerobic variants
    e. Parasitic and symbiotic
    f. Chemotaxis

4. Genetics of Prokaryotic Cells
    a. Existence of plasmids - extragenomic DNA
    b. Transformation - incorporation of DNA fragments, from an external medium, into bacterial genome
    c. Conjugation
    d. Transposons (also present in eukaryotes)

5. Virus Structure
    a. General structural characteristics - nucleic acid and protein, enveloped and non-enveloped
    b. Lack organelles and nucleus
    c. Structural aspects of a typical bacteriophage
    d. Genomic content - RNA or DNA
    e. Size relative to bacteria and eukaryotic cells

6. Viral Life Cycle
    a. Self-replicating biological units that must reproduce within specific host cells
    b. Generalized phage and animal virus life cycles - attachment to host, penetration of cell membrane or cell wall, and entry of viral genetic material; use of host synthetic mechanism to replicate viral components; self-assembly and release of new viral particles
    c. Transduction - transfer of genetic material by viruses
    d. Retrovirus life cycle - integration into host DNA, reverse transcriptase, and HIV
    e. Prions and viroids - sub-viral particles

C. Cell Division, Differentiation, and Specialization

Category 2C focuses on the processes of cell and nuclear division, and the mechanisms governing cell differentiation and specialization. The ability of organisms to reproduce their own kind is the characteristic that best distinguishes living things. In sexually reproducing organisms, the continuity of life is based on the processes of cell division and meiosis. The process of cell division is an integral part of the cell cycle. The progress of eukaryotic cells through the cell cycle is regulated by a complex molecular control system. Malfunctions in this system can result in unabated cellular division, and ultimately the development of cancer.

In the embryonic development of multicellular organisms, a fertilized egg gives rise to cells that differentiate into many different types of cells, each with a different structure, corresponding function, and location within the organism. During development, spatial–temporal gradients in the interactions between gene expression and various stimuli result in the structural and functional divergence of cells into specialized structure, organs, and tissues. The interaction of stimuli and genes is also explained by the progression of stem cells to terminal cells.

The content in this category covers the cell cycle; the causes, genetics, and basic properties of cancer; the processes of meiosis and gametogenesis; and the mechanisms governing cell specialization and differentiation. The topics and subtopics in this category are the following:

1. Mitosis
   a. Mitotic process - prophase, metaphase, anaphase, telophase, interphase
   b. Mitotic structures - centrioles, asters, spindles; chromatids, centromeres, kinetochores; nuclear membrane breakdown and reorganization; mechanisms of chromosome movement
   c. Phases of the cell cycle - G0, G1, S, G2, M
   d. Growth arrest
   e. Control of the cell cycle and loss of controls in cancer cells

2. Biosignaling
   a. Oncogenes
   b. Apoptosis

3. Reproductive System
   a. Gametogenesis by meiosis
   b. Ovum and sperm - differences in formation; differences in morphology; relative contribution to next generation
   c. Reproductive sequence - fertilization, implantation, development, birth

4. Embryogenesis
    a. Stages of early development - fertilization; cleavage; blastula formation; gastrulation, first cell movements and formation of primary germ layers (endoderm, mesoderm, ectoderm); neurulation
    b. Major structures arising out of primary germ layers
    c. Neural crest
    d. Environment - gene interaction in development

5. Mechanisms of Development
    a. Cell specialization - determination, differentiation, tissue types
    b. Cell-cell communication in development
    c. Cell migration
    d. Pluripotency - stem cells
    e. Gene regulation in development
    f. Programmed cell death
    g. Existence of regenerative capacity in various species
    h. Senescence and aging

IV. Foundational Concept 3 - Tissues and Organs

Complex systems of tissues and organs sense the internal and external environments of multicellular organisms, and through integrated functioning, maintain a stable internal environment within an ever-changing external environment. As a result of the integration of a number of highly specialized organ systems, complex living organisms are able to maintain homeostasis while adapting to a constantly changing environment and participating in growth and reproduction. The interactions of these organ systems involves complex regulatory mechanisms that help maintain a dynamic and healthy equilibrium, regardless of their current state and environment.

A. Nervous System and Endocrine System

Category 3A focuses on the structure and functions of the nervous and endocrine systems and the ways in which the systems work together to coordinate the responses of other body systems to both external and internal stimuli. The nervous and endocrine systems work together to detect external and internal signals, transmit and integrate information, and maintain homeostasis. They do all of this by producing appropriate responses to internal and external cues and stressors. The integration of these systems both with one another, and with the other organ systems, ultimately results in the successful and adaptive behaviors that allow for the propagation of the species.

Animals have evolved a nervous system that senses and processes internal and external information that is used to facilitate and enhance survival, growth, and reproduction. The nervous system interfaces with sensory and internal body systems to coordinate physiological and behavioral responses ranging from simple movements and small metabolic changes to long-distance migrations and social interactions. The physiological processes for nerve signal generation and propagation involve specialized membranes with associated proteins that respond to ligands and/or electrical field changes, signaling molecules and, by extension, the establishment and replenishment of ionic electrochemical gradients requiring ATP.

The endocrine system of animals has evolved to produce chemical signals that function internally to regulate stress responses, reproduction, development, energy metabolism, growth, and various individual and interactive behaviors. The integrated contributions of the nervous and endocrine systems to bodily functions are exemplified by the process whereby the signaling of neurons regulates hormone release, and by the targeting of membrane or nuclear receptors on neurons by circulating hormones.

The content in this category covers the structure, function, and basic aspects of nervous and endocrine systems, and their integration. The structure and function of nerve cells is also included in this category. The topics and subtopics in this category are the following:

1. Nervous System: Structure and Function
    a. Major functions - high level control and integration of body systems; adaptive capability to external influences
    b. Organization of vertebrate nervous system
    c. Sensor and effector neurons
    d. Sympathetic and parasympathetic nervous systems - antagonistic control
    e. Reflexes - feedback loop and reflex arc; role of spinal cord and supraspinal circuits
    f. Integration with endocrine system - feedback control

2. Nerve Cell
    a. Cell body - site of nucleus and organelles
    b. Dendrites - branched extensions of cell body
    c. Axon - structure and function
    d. Myelin sheath, Schwann cells, insulation of the axon
    e. Nodes of Ranvier - propagation of nerve impulse along the axon
    f. Synapse - site of impulse propagation between cells
    g. Synaptic activity - transmitter molecules
    h. Resting potential - electrochemical gradient
    i. Action potential - threshold all-or-none and Na-K pump
    j. Excitatory and inhibitory nerve fibers - summation and frequency of firing
    k. Glial cells and neuroglia

3. Electrochemistry
    a. Concentration cell
    b. Direction of electron flow and Nernst equation

4. Biosignaling
    a. Gated ion channels - voltage and ligand gated
    b. Receptor enzymes
    c. G protein-coupled receptors (GPCR)

5. Lipids
    a. Physical and chemical properties
    b. Steroids
    c. Terpenes and terpenoids

6. Endocrine System: Hormones and Their Sources
    a. Function of the endocrine system - specific chemical control at the cell, tissue, and organ levels
    b. Definitions - endocrine gland and hormone
    c. Major endocrine glands - names, locations, products
    d. Major types of hormones
    e. Neuroendocrinology - relation between neurons and hormonal systems

7. Endocrine System: Mechanisms of Hormone Action
    a. Cellular mechanisms of hormone action
    b. Transport of hormones - blood supply
    c. Specificity of hormones - target tissue
    d. Integration with nervous system - feedback control
    e. Regulation by second messengers

B. Main Organ Systems

Category 3B focuses on the structure and functions of the main organ systems—circulatory, respiratory, digestive, immune, lymphatic, muscular, skeletal, and reproductive—and the ways these systems interact to fulfill their concerted roles in the maintenance and continuance of the living organism.

Animals use a number of highly-organized and integrated organ systems to carry out the necessary functions associated with maintaining life processes. Within the body, no organ system is an island. Interactions and coordination between organ systems allow organisms to engage in the processes necessary to sustain life. For example, the organs and structures of the circulatory system carry out a number of functions, such as transporting nutrients absorbed in the digestive system; gases absorbed from the respiratory system and muscle tissue; hormones secreted from the endocrine system; and blood cells produced in bone marrow to and from cells in the body to help fight disease.

The content in this category covers the structure and function of the major organ systems of the body including the respiratory, circulatory, lymphatic, immune, digestive, excretory, reproductive, muscle, skeletal, and skin systems. Also covered in this category is the integration of these systems and their control and coordination by the endocrine and nervous systems. The topics and subtopics in this category are the following:

1. Respiratory System
   a. General function - gas exchange and thermoregulation; protection against disease and particulate matter
   b. Structure of lungs and alveoli
   c. Breathing mechanisms - diaphragm, rib cage, and differential pressure; resiliency and surface tension effects
   d. Thermoregulation - nasal and tracheal capillary beds; evaporation and panting
   e. Particulate filtration nasal hairs and mucus/cilia system in lungs
   f. Alveolar gas exchange - diffusion and differential partial pressure; Henry's law
   g. pH control
   h. Regulation by nervous control - CO_2 sensitivity

2. Circulatory System
    a. Functions - circulation of oxygen, nutrients, hormones, ions, fluids, removal of metabolic waste
    b. Role in thermoregulation
    c. Four-chambered heart - structure and function
    d. Endothelial cells
    e. Systolic and diastolic pressure
    f. Pulmonary and systemic circulation
    g. Arterial and venous systems - arteries, arterioles, venules, and veins; structural and functional differences; pressure and flow characteristics
    h. Capillary beds - mechanisms of gas and solute exchange; mechanism of heat exchange; source of peripheral resistance
    i. Composition of blood - plasma, chemicals, blood cells; erythrocyte production and destruction, spleen, bone marrow; regulation of plasma volume
    j. Coagulation - clotting mechanisms
    k. Oxygen transport by blood - hemoglobin and hematocrit; oxygen content and oxygen affinity
    l. Carbon dioxide transport and level in blood
    m. Nervous and endocrine control

3. Lymphatic System
    a. Structure
    b. Major functions - equalization of fluid distribution; transport of proteins and large glycerides; production of lymphocytes involved in immune reactions; return of materials to the blood

4. Immune System
    a. Innate (non-specific) vs. adaptive (specific) immunity
    b. Innate immune system cells: macrophages and phagocytes
    c. Adaptive immune system cells: T- and B-lymphocytes
    d. Tissues - bone marrow, spleen, thymus, and lymph nodes
    e. Concept of antigen and antibody
    f. Antigen presentation
    g. Clonal selection
    h. Antigen-antibody recognition
    i. Structure of antibody molecules
    j. Recognition of self vs. non-self and autoimmune diseases
    k. Major histocompatibility complex

5. Digestive System
    a. Ingestion - saliva as lubrication and source of enzymes; ingestion (esophagus and transport function)
    b. Stomach - gross structure; storage and churning of food; low pH, gastric juice, mucal protection against self-destruction; production of digestive enzymes and site of digestion
    c. Liver - structural relationship of liver within gastrointestinal system; production of bile; role in blood glucose regulation; role in detoxification
    d. Bile - function and storage in gall bladder
    e. Pancreas - production of enzymes and their transport to the small intestine
    f. Small intestine - structure (anatomic subdivisions); absorption of food molecules and water; function and structure of villi; production of enzymes and site of digestion; neutralization of stomach acid
    g. Large intestine - gross structure; absorption of water; bacterial flora
    h. Rectum - Storage and elimination of waste (feces)
    i. Muscular control - peristalsis
    j. Endocrine control - hormones and target tissues
    k. Nervous control - enteric nervous system

6. Excretory System
    a. Roles in homeostasis - blood pressure; osmoregulation; acid-base balance; removal of soluble nitrogenous waste
    b. Kidney structure - cortex and medulla
    c. Nephron structure - glomerulus, Bowman's capture, proximal tubule, Loop of Henle, distal tubule, collecting duct
    d. Formation of urine - glomerular filtration; secretion and reabsorption of solutes; concentration of urine; counter-current multiplier mechanism
    e. Storage and elimination - ureter, bladder, urethra
    f. Osmoregulation - capillary reabsorption of water, amino acids, glucose, ions
    g. Muscular control - sphincter muscle

7. Reproductive System
    a. Male and female reproductive structures and their functions - gonads and genitalia; differences between male and female structures
    b. Hormonal control of reproduction - male and female sexual development; female reproductive cycle; pregnancy, parturition, lactation; integration with nervous system

8. Muscle System
    a. Important functions - support and mobility; peripheral circulatory assistance; thermoregulation (shivering reflex)
    b. Structure of three basic muscle types - striated, smooth, and cardiac
    c. Muscle structure and control of contraction - T-tubule system; contractile apparatus; sarcoplasmic reticulum; fiber type; contractile velocity of different muscle types
    d. Regulation of cardiac muscle contraction
    e. Oxygen debt and fatigue
    f. Nervous control - motor neurons; neuromuscular junction and motor end plates; sympathetic and parasympathetic innervation; voluntary and involuntary muscles

9. Specialized Cell - Muscle Cell
    a. Structural characteristics of striated, smooth, and cardiac muscle
    b. Mitochondria abundance in red muscle cells - ATP source
    c. Organization of contractile elements - actin and myosin filaments, cross-bridges, sliding filament model
    d. Sarcomeres - I and A bands, M and Z lines, H zone
    e. Presence of troponin and tropomyosin
    f. Calcium regulation of contraction

10. Skeletal System
    a. Functions - structural rigidity and support; calcium storage; physical protection
    b. Skeletal structure - specialization of bone types and structures; joint structures; endoskeleton vs. exoskeleton
    c. Bone structure - calcium-protein matrix; cellular composition of bone
    d. Cartilage - structure and function
    e. Ligaments and tendons
    f. Endocrine control

11. Skin System
    a. Structure - layer differentiation and cell types; relative water-impermeability
    b. Functions in homeostasis and osmoregulation
    c. Functions in thermoregulation - hair and erectile musculature; fat layer for insulation; sweat glands and location in dermis; vasoconstriction and vasodilation in surface capillaries
    d. Physical protection - nails, calluses, hair; protection against abrasion and disease organisms
    e. Hormonal control - sweating, vasodilation, vasoconstriction