

Physiology Learning Outcomes

Spring 2023

(Indexes added October 2025)



Introduction to the HAPS Physiology Learning Outcomes (PLOs)

This is a brief introduction to the HAPS Physiology Learning Outcomes (PLOs). A more detailed description of the organization of the PLO modules, how to use them, and how they were developed may be found on the *HAPSweb.org* website.

Introduction

The HAPS physiology learning outcomes (PLOs) are an exhaustive list of potential topics that might be included in a one-semester introductory undergraduate physiology course.

- These learning outcomes are far more comprehensive than any student can learn in one term or semester. Instructors will need to select the topics and outcomes that are appropriate for their course and their students.
- There is no single set of learning outcomes recommended for an introductory physiology course because of the variability in teaching goals and student populations that exist at different institutions.

Select the PLOs you wish to cover in your course, knowing that not all the PLOs in a module may be suitable for your students. The PLOs are necessarily broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate modules and details for your course.

Organization of the HAPS Physiology Learning Outcomes

The Modules

The HAPS PLOs are organized into 19 modules that use a competency-based approach for student skill development as well as physiology content acquisition:

- Module 1: Skills that students should be acquiring during their undergraduate studies
- Module 2: Entering Competencies (EC) – ideally these are acquired prior to beginning physiology, but some of them may need to be addressed in the physiology course
- Module 3: Core Concepts (CC) of Physiology – the fundamental themes that appear repeatedly in multiple body systems
- Modules 4-19 (A-O): organ systems physiology and related concepts

The learning outcomes in each module are mapped (when possible) to the key skills and core concepts represented by the learning outcomes. Indexes of the skills and core concepts mapping are available at the end of this document.

The expert panel that wrote the HAPS Physiology Learning Outcomes was assembled from respondents to a HAPS call for volunteers in summer 2019. Members were selected to represent the broad range of institutions found in the HAPS membership. Volunteers who were not selected for the panel were invited to serve on the PLO Advisory Board in November 2022.

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Physiology Skills Summary

The following skills are aspirational. It is up to instructors to select the skills most relevant to their course.

- Learning outcomes in the PLO documents are coded to indicate which learning outcomes might be used to teach a particular skill. **We have limited the coding to the 6 skills highlighted in yellow.** Many of the other skills we assume all students should acquire during their studies, and therefore these codes are not used in the PLO modules. For example, we assume that students will learn to communicate their knowledge and understanding effectively (Com-1). Some advanced skills are instructor-option.
- The skills here are adapted with permission from *The BioSkills Guide - a Tool for Interpreting the Vision and Change Core Competencies* - (Clemmons et al. 2020)

At the end of an introductory one-semester physiology course, a student should be able to do the following:	
Process of Science (PS)	
PS-1	Draw conclusions based on inference and evidence-based reasoning.
PS-2	Interpret, summarize, and evaluate evidence, and apply these abilities to critique claims from sources outside the classroom (e.g., scientific articles, popular media, medical websites).
PS-3	Evaluate and apply new evidence to critique, revise, or support physiological models.
PS-4	Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions.
Quantitative Reasoning (QR)	
QR-1	Correctly perform basic calculations (e.g., percentages, frequencies, rates, means, unit conversions, exponents, logarithms).
QR-2	Select and use appropriate mathematical relationships to solve problems.
QR-3	Apply knowledge of physiological ranges to evaluate quantitative results.
QR-4	Describe how physiologists and healthcare professionals use quantitative reasoning to evaluate physiological function.

QR-5	Create and/or interpret graphs and other quantitative representations of physiological processes.
QR-6	Interpret the significance of physiological results within normal limits (WNL) or outside, based on human variability.
Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)	
MS-1	Explain how a simplified model can represent a physiological process, system or disease, and give an example.
MS-2	Given a representation (model) of a physiological process or system, evaluate the representation's strengths, limitations, and assumptions.
MS-3	Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease.
MS-4	Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works.
Interdisciplinary Nature of Physiology (I)	
I-1	Given a physiological process, apply relevant concepts from other disciplines such as chemistry, physics, and other areas of biology (e.g., genetics).
I-2	Incorporate concepts from other STEM disciplines into models or explanations of physiological processes.
I-3	Describe specific examples of real-world problems that are too complex to be solved by applying physiological approaches alone and that require a multidisciplinary approach.
Communication and Collaboration (Com)	
Com-1	Use appropriate language, style, and modes (e.g., oral, written, visual) to communicate physiology and its real-world applications effectively to targeted audiences (e.g., general public, physiology experts, collaborators in other disciplines).
Com-2	Work collaboratively in diverse teams (e.g., lab partners, healthcare workers) to solve problems.
Com-3	Elicit, listen to, and incorporate ideas from teammates with diverse and different perspectives and backgrounds.
Com-4	Critique others' work and ideas constructively and respectfully.

Metacognition (Me)

These items are global and will not be mapped to specific PLOs but may be assessed in other ways by instructors (e.g., exam wrappers, peer evaluation, reflections).

Me-1	Apply a variety of evidence-based study strategies in the learning of physiology, periodically assess their personal efficacy, and revise their study approach when appropriate.
Me-2	Elicit and evaluate constructive feedback from others to appropriately revise work, study strategies, or behavior.
Me-3	Evaluate their own understanding and skill level, recognize gaps in their own knowledge and understanding, and seek help when needed.
Me-4	Develop and demonstrate the ability to set achievable personal goals; prioritize tasks; identify necessary skills, resources, and study strategies; meet deadlines; work independently; and adapt to change.

Science and Society (SS)

SS-1	Critique how ethical controversies in physiological and medical research have been and continue to be addressed by the scientific community.
SS-2	Describe examples of how scientists' backgrounds and biases can influence science and public health, and how science is enhanced through diversity.
SS-3	Provide examples and describe how systemic factors (e.g., socioeconomic, political, sex and gender, ethnicity) both influence and limit our current understanding of physiological processes in our diverse and largely under-studied populations.
SS-4	Apply evidence-based reasoning and physiological knowledge in daily life (e.g., consuming popular media, deciding how to vote).
SS-5	Describe the roles and responsibilities of research scientists, scientist-educators, and clinicians in facilitating accurate, evidence-based information and models to inform public understanding of physiology and health.

References

Clemmons A, Timbrook J, Herron J, Crowe A. 2020. **BioSkills Guide**. Core Competencies for Undergraduate Biology, (Version 5.0). QUBES Educational Resources. doi:10.25334/156H-T617

PLO EC Entering Competencies

The competencies listed here are concepts we expect students to know upon entering their first physiology course. For some student populations, it may be necessary to teach or review introductory biology and/or general chemistry concepts at the beginning of the course. We recognize that using course time to teach entering competencies may limit time for teaching some physiology concepts later.

Terminology:

In subsequent modules, we will use the term *cell membrane* instead of *plasma membrane*. The word *plasma* in physiology/medicine means the fluid matrix of the blood, and some students start thinking there are membranes in the blood, so we usually restrict the term *plasma* to the fluid compartment and simply refer to cell membranes when discussing phospholipid bilayers of cells.

At the beginning of an introductory one-semester physiology course, a student should be able to do the following:

EC-1 Atoms and molecules

EC.1.1	Compare and contrast states of matter (e.g., solid, liquid, gas).
EC.1.2	Compare and contrast atoms, elements, molecules, compounds, and mixtures.
EC.1.3	Explain the relationship between the number of electrons in an atom's electron shell, its chemical stability, and the atom's ability to form chemical bonds.
EC.1.4	Compare and contrast ions, salts, electrolytes, free radicals, isotopes, and radioisotopes.

EC-2 Biological energy

EC.2.1	Define <i>energy</i> and list different forms of energy (e.g., light, heat, mechanical, chemical).
EC.2.2	Compare and contrast potential energy and kinetic energy.
EC.2.3	Describe how energy in different forms can be acquired by biological systems and stored (e.g., chemical bonds, gradients).
EC.2.4	Define <i>work</i> (work = force x distance) in words.
EC.2.5	Describe biological examples of how energy is used for chemical work, transport work, and mechanical work.
EC.2.6	State the first law of thermodynamics (law of conservation of energy) and explain how it applies to systems that can exchange energy with their environment, such as the human body.
EC.2.7	Explain the relationships among energy, maintaining a state of order, and entropy (i.e., the second law of thermodynamics).

EC-3 Chemical bonds and reactions	
EC.3.1	Explain the mechanisms of covalent, ionic, and hydrogen bonds, and list biologically relevant examples of each.
EC.3.2	Compare and contrast nonpolar and polar covalent bonds.
EC.3.3	Compare the relative strengths (i.e., the amount of energy needed to break the bond) for the following types of bonds in biological systems: nonpolar covalent, polar covalent, ionic, and hydrogen bonds.
EC.3.4	Explain the relationships among the types of bonds in a molecule and describe how bonds contribute to molecular shape.
EC.3.5	Define and explain the relationships among <i>chemical reaction</i> , <i>reactant</i> , <i>substrate</i> , and <i>product</i> .
EC.3.6	Define the <i>reaction rate</i> of a reaction and list typical units.
EC.3.7	Apply the concept of <i>equilibrium</i> to a chemical reaction, such as $A + B \leftrightarrow C + D$.
EC.3.8	Explain why some chemical reactions will occur spontaneously when the reactants are brought together but other reactions will not (e.g., the activation energy of reactions).
EC.3.9	Explain the role of catalysts in chemical reactions.
EC-4 Organic compounds	
EC.4.1	Compare and contrast organic and inorganic molecules and give examples of each.
EC.4.2	List the most important biological ions and write their chemical notation (e.g., sodium ion = Na^+ , bicarbonate ion = HCO_3^-).
EC.4.3	List the 4 most common functional groups in biology and write their chemical notation (i.e., amino $-\text{NH}_2$, hydroxyl $-\text{OH}$, carboxyl $-\text{COOH}$, and phosphate $-\text{H}_2\text{PO}_4$).
EC.4.4	Define <i>monomers</i> and <i>polymers</i> , then list examples of each.
EC.4.5	Compare and contrast the general molecular structure and properties of the 4 classes of biomolecules (carbohydrates, proteins, lipids, and nucleic acids).
EC.4.6	Describe the building blocks of the 4 classes of biomolecules and explain how these building blocks combine to create complex molecules (e.g., amino acids linked through peptide bonds become peptides and proteins with primary, secondary, tertiary, and/or quaternary structure).
EC-5 Biological reactions	
EC.5.1	Explain the relationships among activation energy, endergonic and exergonic reactions, and reversible and irreversible reactions.
EC.5.2	Explain the role of adenosine triphosphate (ATP) in the cell.
EC.5.3	Diagram or describe the reversible reaction for adenosine triphosphate (ATP) synthesis from adenosine diphosphate (ADP) and inorganic phosphate (P_i), and the release of energy from hydrolysis of ATP to adenosine diphosphate (ADP) and inorganic phosphate (P_i).
EC.5.4	Explain how reactions can be coupled to drive an endergonic reaction, and diagram or describe an example.

EC.5.5	Given examples of biological reactions, classify them as one of the following reaction types: dehydration/hydrolysis, oxidation/reduction, or transfer of chemical groups (exchange, addition, subtraction).
EC.5.6	Explain the role of enzymes in biological reactions.
EC.5.7	Describe the characteristics of enzymes and how various factors affect enzyme activity (e.g., temperature, pH, enzyme concentration).
EC.5.8	Define <i>protein binding sites</i> and <i>ligands</i> , and diagram or describe how they function in a protein-binding reaction.
EC.5.9	Define <i>affinity</i> , <i>competition</i> , <i>saturation</i> , and <i>specificity</i> in the context of protein-binding reactions.
EC-6 Solutions and solubility	
EC.6.1	Describe the characteristics of water (molecular size, shape, and polarity).
EC.6.2	Compare and contrast <i>solutions</i> , <i>solutes</i> , and <i>solvents</i> .
EC.6.3	Compare and contrast <i>hydrophobic</i> and <i>hydrophilic</i> molecules.
EC.6.4	Explain how the polarity of water facilitates the dissociation of salts (such as NaCl) and the solubility of other polar and charged molecules.
EC.6.5	Define and contrast units used to describe concentrations of solutions (e.g., mM, mEq/L, mg/dL, mg%).
EC.6.6	Define <i>pH</i> , <i>acid</i> , <i>base</i> , and <i>buffer</i> .
EC.6.7	Explain the relationship between pH and hydrogen ion concentration.
EC.6.8	Given the pH of a solution, identify it as acidic, neutral, or alkaline (basic).
EC-7 General organization of a cell	
EC.7.1	Describe the general functions of the plasma [cell] membrane, cytoplasm, and nucleus of an animal cell.
EC.7.2	Describe the structures and functions of the major intracellular components, including membrane-bound organelles.
EC.7.3	Compare and contrast cytoplasm and cytosol.
EC.7.4	Describe the basic structures and roles of the cytoskeleton.
EC-8 Cellular membrane structure and function	
EC.8.1	Diagram and describe the structure of cellular membranes, including their composition and arrangement of lipids, proteins, and carbohydrates.
EC.8.2	Explain how the distribution of lipids and proteins in a cell membrane influences membrane permeability.
EC.8.3	Define <i>osmosis</i> and list an example of the conditions under which osmosis occurs.
EC-9 Genes, genomes, and gene expression	
EC.9.1	Describe the <i>gene</i> as the unit of heredity.
EC.9.2	Define a <i>genome</i> and explain the relationship of genes and chromosomes in a genome.

EC.9.3	Explain the process of protein synthesis using DNA, RNA and ribosomes and the concepts of genetic code, transcription, and translation.
EC.9.4	Explain how differential expression of genes gives rise to different cell types.
EC-10 Cellular respiration (introduction)	
EC.10.1	Define <i>cellular respiration</i> and describe the process as a chemical reaction with reactants and products (e.g., glucose + oxygen $\rightarrow$. . . or $C_6H_{12}O_6 + O_2 \rightarrow \dots$).
EC.10.2	Describe an overview of the pathways by which glucose is converted to carbon dioxide and water (e.g., glycolysis, citric acid [Krebs or tricarboxylic acid] cycle, electron transport system), including starting compound(s), product(s), and the net yield of ATP for each pathway.
EC.10.3	Explain the role of oxygen as the final electron acceptor in the aerobic respiration pathway.

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in D.1.12*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts and are not appropriate for all introductory physiology classes.

PLO CC Core Concepts

Module CC Core Concepts introduces learning outcomes and ideas central to the discipline of physiology.

PLEASE NOTE: The detailed learning outcomes here are end-of-semester competencies, and their inclusion in this first module does not indicate that all these learning outcomes must be introduced at the beginning of a course. Students can be introduced to the key themes at the start and be alerted to the fact that the details of these concepts will appear repeatedly throughout the course. Many of the detailed learning outcomes presented in Module CC can be taught at any point in the semester, whenever the related content is first presented.

The core concepts of Module CC are continued with additional detail in Module A *Cell Physiology & Membrane Processes* and Module B *Cell-Cell Communication & Control Systems*. The subsequent modules C-P are specific system-based or concept-based modules, with boxes indicating which core concepts found in this module are required prior knowledge for successful study in that module.

The four tissue types central to anatomy are not always taught explicitly in introductory biology or an introductory physiology course. Because epithelia and epithelial transport are a repeating theme across many systems, we have included them here in Module CC, section CC-1 *Structure-Function Relationships*. Muscle and neural tissue are covered in detail in subsequent modules (Modules D, E, and F). Connective tissue is discussed wherever appropriate.

PLO CC Core Concepts	
At the end of an introductory one-semester physiology course, a student should be able to do the following:	
CC-1 Structure-Function Relationships (Additional detail can be found in Module A <i>Cell Physiology & Membrane Processes</i>)	
	Anatomy and levels of organization
CC.1.1	Describe, in order from simplest to most complex, the major levels of organization in the body, and list examples of each.
CC.1.2	List the physiological systems of the human body, their major components, and the major functions of each.
CC.1.3	Describe, compare and contrast the general features and functions of the four major tissue types (muscle, connective, neural, and epithelial).
CC.1.4	Describe, compare and contrast epithelial tissues based on structural characteristics (e.g., cell shape, cell junctions) and function (e.g., transporting), and give an example and location of each type.
CC.1.5	Compare and contrast the structure and function of exocrine and endocrine glands.
CC.1.6	Apply the concepts of agonists and antagonists across levels of organization in the body (e.g., cell signaling, functional muscle groupings).
CC.1.7	Apply the concepts of convergence and divergence across levels of organization in the body (e.g., organization of the vasculature, neurons in neural networks, amplification in chemical signaling pathways, multiple ligands binding to the same receptor).
	Compartmentation
CC.1.8	Define <i>compartmentation</i> and describe examples of compartments in the body across levels of organization.
CC.1.9	Explain the adaptive advantages and challenges of compartmentation in the body (e.g., separating metabolic processes, moving materials between compartments).
CC.1.10	Compare and contrast the ways different compartments in the body are distinguished from each other (e.g., physical separation, chemical composition, volume).
CC.1.11	Compare and contrast the methods by which substances move between compartments in the body and name an example of a compartment that has multiple routes for entry or exit.
CC.1.12	Describe how changes in the size or shape of a structure alter the surface-to-volume ratio of the structure, and list biological examples of how modifications in surface area change the surface-to-volume ratio (e.g., microvilli on the surface of a cell).
	Mass balance and energy balance
CC.1.13	Explain the impact of rates of inflow and outflow on the load of mass or amount of energy in a compartment.
CC.1.14	Relate the law of conservation of mass or conservation of energy to inflow, outflow, and storage of mass or energy.

	Molecular structure and function
CC.1.15	Explain how the four major classes of biomolecules can combine to form complex molecules (e.g., phospholipids).
CC.1.16	Describe the relationship between molecular structure and function.
CC.1.17	Explain how the properties of molecules (e.g., functional groups, polarity, charge, shape) influence their interactions with each other and with ions.
CC.1.18	Explain factors that influence the specificity and affinity of protein-ligand interactions (e.g., molecular shape, charge, electronegativity).
CC.1.19	Describe multiple physiological processes that involve proteins binding to ligands (e.g., enzymatic reactions and function of isozymes, molecular signaling, membrane transport, antibody defenses).
CC.1.20	Explain the concept of saturation of protein binding sites and describe how saturation can influence the rate of a physiological process.
CC.1.21	Describe how the quantity of binding sites and relative ligand concentration relate to the saturation of protein binding sites and provide an example.
CC.1.22	Describe physiological or pharmacological examples of molecular competition.
	Properties of physical systems
CC.1.23	Describe and explain the reciprocal (inverse) relationship between elastance and compliance.
CC.1.24	Describe the impact of a lever system on the amplification of force and describe an example.
CC.1.25	Describe and explain the impact of viscosity on fluid flow.
CC.1.26	Explain the relationship between pressure and volume for a compressible fluid (e.g., air) versus a noncompressible fluid (e.g., water).
CC.1.27	Describe how structures can be linked together mechanically at different levels of organization (e.g., protein-protein interactions, cell-cell junctions, tendons between muscles and bone).
CC-2 Homeostasis and Control Pathways (Additional detail in Module B, Cell-Cell Communication & Control Systems)	
	Homeostasis
CC.2.1	Define homeostasis and explain its importance for body function.
CC.2.2	Compare and contrast equilibrium and steady state, then explain and list an example of how a system can be a steady-state disequilibrium.
CC.2.3	Explain the roles of the following in maintaining body homeostasis: setpoint and acceptable range, regulated (monitored) variable, controlled variable, negative feedback.
CC.2.4	List physiological variables for which the body attempts to maintain homeostasis (e.g., plasma glucose concentration) and variables that are not subject to homeostatic regulation (e.g., plasma cholesterol concentration), then explain why each variable belongs in the given category.

CC.2.5	Compare a regulated and controlled variable by describing a generalized model of a process subject to homeostatic regulation (e.g., heart rate is controlled to regulate blood pressure. Sensors exist for blood pressure, but no sensors specifically monitor heart rate.).
CC.2.6	Explain how the principle of mass balance and homeostasis are interrelated and describe an example in the body.
CC.2.7	Describe physiological processes or parameters that cycle in a predictable fashion over a period of time (e.g., daily, monthly).
Control pathways (more detail in Module B)	
CC.2.8	List the steps of a physiological reflex from stimulus to response using a control system model (i.e., input, control center, output).
CC.2.9	Compare and contrast negative feedback, positive feedback, and feedforward in terms of the relationship between stimulus and response and describe examples of each.
CC.2.10	Predict outcome(s) when a response pathway is altered or disrupted.
CC.2.11	Given a change in the response of a pathway, predict which component(s) of the pathway may have been altered or disrupted.
CC.2.12	Apply knowledge of the steps of a physiological reflex to the components of a given example, then determine if the reflex is associated with the maintenance of homeostasis.
CC-3 Gradients and Flow	
CC.3.1	Describe how a gradient determines flow between two regions, and list examples of concentration, osmotic, pressure, or electrical gradients that exist across levels of organization in the body.
CC.3.2	Compare velocity of flow and rate of flow (flux), and state representative units of each.
CC.3.3	Predict how changes in a gradient will affect flow along the gradient.
CC.3.4	Predict how differences in resistance will affect flow.
CC.3.5	Predict the direction and magnitude of flow in the presence of two opposing gradients.
CC-4 Energy Types, Storage, Use and Conversion	
CC.4.1	Compare and contrast physiologically relevant forms of energy (e.g., potential and kinetic; chemical, mechanical, electrical).
CC.4.2	Identify and list biological examples in which energy is converted from one form to another.
CC.4.3	Compare and contrast different forms of biological work and provide examples.
CC.4.4	Compare and contrast the forms of short-term and long-term energy storage in the body.
CC.4.5	Compare and contrast the relative amounts of chemical bond energy stored in different molecules (e.g., lipids, ATP, glycogen).
CC.4.6	Explain the relationship between the magnitude of a concentration, osmotic, pressure, or electrical gradient and the potential energy stored in that gradient.
CC.4.7	Describe processes that require energy in the body across all levels of organization (e.g., muscle contraction, transport across membranes).
CC.4.8	Explain what is meant by <i>the efficiency of a biochemical reaction</i> and list examples of its importance in physiology.

CC-5 Communication	
CC.5.1	Explain the importance of coordinated communication of information in the body.
CC.5.2	Define <i>transduction</i> and explain its role in communication (e.g., cell signaling, hearing).
CC.5.3	Explain different ways information is coded to serve unique functions (e.g., genetic code, coding of sensory information, molecular modification).
CC.5.4	Explain how information can be converted from one form to another (e.g., DNA to proteins, sound waves to action potentials, extracellular signals to intracellular signals).
CC-6 Systems Integration	
CC.6.1	Define <i>integration of function</i> within and across physiological systems at all levels of organization.
CC.6.2	Describe how one body structure can participate in or regulate the function of multiple body systems (e.g., role of the pancreas in the digestive and endocrine systems).
CC.6.3	Explain how multiple organ systems can work together to maintain homeostasis.
CC.6.4	Explain how multiple organ systems can work together in non-homeostatic processes (e.g., during pregnancy, stress response).
CC.6.5	Describe how change in one organ system can affect the functioning of other organ systems.
CC.6.6	Apply physiological knowledge to predict outcomes when system integration is altered or disrupted (e.g., predict what happens to neuronal membrane potential when extracellular fluid K^+ concentration decreases).

MODULE CC Core Concepts

BACKGROUND BASICS: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies (EC) from introductory biology and chemistry

- EC-1 Atoms and molecules (EC.1.1, EC.1.3)
- EC-2 Biological energy (EC.2.1, EC.2.2, EC.2.3, EC.2.4)
- EC-3 Chemical bonds and reactions (EC.3.1, EC.3.2, EC.3.4, EC.3.7)
- EC-4 Organic compounds (EC.4.3, EC.4.5, EC.4.6)
- EC-5 Biological reactions (EC.5.2, EC.5.3, EC.5.8, EC.5.9)
- EC-6 Solutions and solubility (EC.6.1, EC.6.3, EC.6.4)
- EC-7 General organization of a cell (EC.7.1, EC.7.2)
- EC-8 Cellular membrane structure and function (EC.8.1, EC.8.2, EC.8.3)
- EC-9 Genes, genomes, and gene expression (EC.9.1, EC.9.3)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
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- Advanced learning outcomes are indicated with an asterisk, as in A.3.7*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO A Cell Physiology & Membrane Processes

Module A Cell Physiology & Membrane Processes is a continuation of the core competencies in Module CC. It includes concepts related to basic cell physiology that will appear in and be referenced in most subsequent systems modules. The basic properties of membrane transport, body fluid compartments, osmolarity and tonicity, and resting membrane potential are covered here.

Terminology: Here and in subsequent modules, the term *cell membrane* is used instead of *plasma membrane*. *Plasma* in physiology/medicine is defined as the fluid matrix of the blood. In an effort to promote clarity and prevent student confusion (i.e., students thinking there are membranes in the blood), the term *plasma* is restricted to discussion of the fluid compartment and *cell membrane* is used to refer to the phospholipid bilayer of the cell.

To clarify membrane terminology further, in anatomy/histology, a *membrane* is defined as a thin sheet of tissues that serves as a covering or barrier between body compartments (e.g., cutaneous or serous membranes). Alert students to the difference between a *cell membrane* and tissue *membranes* in subsequent modules.

CORE CONCEPTS from Module CC: Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.4, CC.1.6)

Compartmentation (CC.1.8-CC.1.12)

Mass and energy balance (CC.1.13-CC.1.14)

Molecular structure and function (CC.1.15-CC.1.22)

Properties of physical systems (CC.1.27)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.1-CC.2.2)

CC-3 Gradients and Flow (CC.3.1, CC.3.3)

CC-4 Energy Types, Storage, Use and Conversion (CC.4.1-CC.4.3, CC.4.6-CC.4.7)

CC-5 Communication (CC.5.2-CC.5.4)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (A.2.11, A.4.8, A.6.8)

PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (A.2.10, A.6.3, A.6.10, A.7.7, A.7.12, A.7.13, A.7.14)

Quantitative Reasoning (QR)

QR-2 Select and use appropriate mathematical relationships to solve problems. (A.3.8, A.3.9, A.6.5, A.7.11)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (A.7.8)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (A.3.1, A.4.1, A.4.5, A.7.15)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (A.4.7)

PLO A Cell Physiology & Membrane Processes			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
A-1 Cell Membrane Structure and Function			
A.1.1	Describe the functions of membrane proteins (e.g., structural proteins, <i>receptor proteins</i> , <i>channels</i>).	CC.1.8, CC.1.11 CC.1.18, CC.4.2 CC.5.2, CC.5.4	
A.1.2	Describe the functions of membrane-associated carbohydrates (e.g., glycocalyx, glycolipids).	CC.1.15, CC.1.16	
A-2 Movement of Materials across Cell Membranes			
A.2.1	Explain the <i>selective permeability of cell membranes</i> , and list examples of permeable and impermeable molecules.	CC.1.8, CC.1.11 CC.1.16, CC.1.17	
A.2.2	Explain the importance of selective permeability in the maintenance of homeostasis.	CC.2.1 CC.2.6	
A.2.3	Explain how changes in the concentration gradient, surface area, lipid solubility, and molecular size affect the <i>rate of diffusion</i> of substances across a membrane [Fick's Law of diffusion].	CC.1.12, CC.1.16 CC.3.1, CC.3.3 CC.4.6	
A.2.4	Compare and contrast <i>active transport</i> and <i>passive transport</i> across cell membranes (e.g., energy source, gradients).	CC.1.9, CC.1.11 CC.1.13, CC.4.1 CC.4.2, CC.4.6 CC.4.7	
A.2.5	Compare and contrast the structural and functional differences of <i>membrane channel</i> proteins and <i>membrane transporter</i> proteins.	CC.1.9 CC.1.11 CC.1.16	
A.2.6	Explain the role of protein-binding <i>affinity</i> , <i>specificity</i> , <i>competition</i> , and <i>saturation</i> in protein-mediated transmembrane transport.	CC.1.6 CC.1.19, CC.1.20 CC.1.21, CC.1.22	
A.2.7	Compare and contrast the properties of <i>leak channels</i> and <i>gated channels</i> (ligand-, voltage-, and mechanically gated), and provide examples of each, including the substance(s) transported through the channel.	CC.1.16, CC.5.4	

A.2.8	Compare and contrast the membrane transport processes of <i>simple diffusion</i> , <i>facilitated diffusion</i> , <i>primary (direct) active transport</i> , and <i>secondary (indirect) active transport</i> with respect to the direction of movement relative to the concentration gradient, the energy source for the movement, the properties of the substance(s) transported (e.g., size and polarity), and whether a transport protein is involved, including examples of each.	CC.1.9 CC.1.13 CC.1.16 CC.1.17 CC.3.1, CC.4.2 CC.4.6, CC.4.7	
A.2.9	Compare and contrast modes of transmembrane <i>vesicular transport</i> (e.g., <i>exocytosis</i> , <i>endocytosis</i> , <i>phagocytosis</i>) with respect to their mechanisms, the direction of movement, the type of material being moved, and the energy source for the movement.	CC.1.9, CC.1.11 CC.4.2, CC.4.7	
A.2.10	Use the properties of a molecule or ion to predict if the substance can cross a cell membrane by simple diffusion or if a membrane transport protein or vesicle is required.	CC.1.9, CC.1.11, CC.1.13 CC.1.16	PS-4
A.2.11	Use the properties of a molecule or ion and its distribution across a membrane to predict which type(s) of transport it can utilize.	CC.1.9 CC.1.11, CC.1.13 CC.1.16 CC.3.1, CC.4.3 CC.4.7	PS-1
A-3 Body Fluid Compartments			
A.3.1	Draw and label or describe a box diagram of the body showing its subdivision into <i>extracellular fluid</i> (ECF), <i>plasma</i> , <i>interstitial fluid</i> (IF), and <i>intracellular fluid</i> (ICF).	CC.1.8	MS-3
A.3.2	Describe the structures that separate body fluid compartments and list the transport mechanisms by which water and other substances move between compartments.	CC.1.8, CC.1.9 CC.1.13	
A.3.3	Explain the influence of body composition on <i>total body water</i> (TBW) volumes of healthy adults.		
A.3.4	Compare and contrast the relative volumes and osmolarities of intracellular fluid (ICF) and extracellular fluid (ECF).	CC.1.8	
A.3.5	Describe the relative distribution of the following ions between the intracellular fluid (ICF) and extracellular fluid (ECF): Na ⁺ , K ⁺ , Cl ⁻ , and Ca ²⁺ .	CC.1.10	

A.3.6	Describe the structure separating the plasma and interstitial fluid (IF) and compare the volumes and solute composition of the two compartments.	CC.1.8	
A.3.7*	Identify the compounds used as indicators to measure the volumes of different body compartments (e.g., inulin for the ECF).		
A.3.8*	Use results from indicator dilution studies to calculate plasma volume, blood volume, extracellular fluid (ECF) volume, and total body water volume.	CC.1.14	QR-2
A.3.9*	Given a person's body weight and percent body fat, calculate approximate values for total body water volume, lean body mass, extracellular fluid volume, intracellular fluid volume, blood volume, and plasma volume.		QR-2
A-4 Epithelial Transport			
A.4.1	Diagram or describe a simple epithelium, labeling <i>tight junctions</i> , <i>apical membrane</i> , and <i>basolateral membrane</i> , and using arrows to show the movement of compounds across the epithelium by the <i>transcellular pathway</i> and <i>paracellular pathway</i> .	CC.1.4, CC.1.27	MS-3
A.4.2	Explain the functional significance of having different transport proteins on the apical and basolateral membranes of an epithelial cell (<i>polarized distribution</i>) (e.g., the distribution of membrane proteins in an intestinal epithelial cell).	CC.1.4, CC.1.9	
A.4.3	Compare and contrast the structures and functions of <i>leaky epithelia</i> and <i>tight epithelia</i> and provide examples.	CC.1.4	
A.4.4	List examples of epithelial transport between body compartments and between the external and internal environments.	CC.1.9, CC.1.11	
A.4.5	Diagram or describe the <i>Na⁺-dependent transport of glucose</i> across an epithelium, labeling apical and basolateral membranes, the solute and ion concentration gradients between compartments, and the membrane transport proteins involved.	CC.1.11 CC.4.2, CC.4.7	MS-3
A.4.6	Define <i>transcytosis</i> , explain how it is used to move materials across an epithelium, and provide an example (e.g., movement of proteins across the capillary endothelium).	CC.1.4	

A.4.7	Apply the principles of epithelial transport to design an epithelium with specific transport properties and appropriate membrane transport proteins (e.g., absorption of calcium ions in the small intestine).	CC.1.4, CC.4.2 CC.4.7	MS-4
A.4.8*	Explain how Na ⁺ -glucose cotransport across the intestinal epithelium enhances water absorption in oral rehydration procedures.	CC.3.1, CC.3.3	PS-1
A-5 Water Movement across Membranes			
A.5.1	Describe the forces that move water across biological membranes (e.g., hydrostatic pressure, osmotic pressure) and the role of aquaporins in transmembrane water transport.	CC.3.1	
A.5.2	Compare and contrast osmosis with simple diffusion of solutes across membranes.	CC.3.1	
A.5.3	Explain how solute transport across a membrane can drive water movement across the membrane.	CC.3.1	
A-6 Osmolarity and Tonicity			
A.6.1	Compare and contrast mole, osmole, molarity, and osmolarity.		
A.6.2*	List the typical value and normal range for human plasma osmolarity.	CC.1.10	
A.6.3	Predict the movement of water between intracellular and extracellular compartments caused by changes in ECF osmolarity.	CC.1.8, CC.1.9 CC.1.11, CC.3.1 CC.3.3	PS-4
A.6.4*	Compare and contrast osmolarity and osmolality.		
A.6.5*	Given a solute's molecular mass and its percent concentration in a solution, calculate the solution's molarity and osmolarity.		QR-2
A.6.6	Explain the difference between osmolarity and tonicity.	CC.1.10	
A.6.7	Describe the effects of hypertonic, isotonic, and hypotonic solutions on a cell's volume at equilibrium.	CC.1.10, CC.3.1 CC.3.3	
A.6.8	Explain why the osmolarity of a solution cannot always be used to predict the solution's tonicity (e.g., how do penetrating and nonpenetrating solutes affect tonicity?), and list examples (e.g., an isosmotic glucose solution is not isotonic to human cells).	CC.1.10	PS-1
A.6.9	Given the composition and osmolarity of a solution, predict whether it will be hypotonic, isotonic, or hypertonic to a typical human cell.	CC.1.8, CC.1.10	

A.6.10*	Predict the changes (increased, decreased, no change) in extracellular volume, extracellular osmolarity, intracellular volume, and intracellular osmolarity caused by intravenous (IV) infusion of 0.9% NaCl, 0.45% NaCl, or 7.5% NaCl into a person with body osmolarity equivalent to 0.9% NaCl.	CC.3.1, CC.3.3	PS-4
A-7 Membrane Potential Differences			
A.7.1	Describe the concept of <i>electrochemical disequilibrium</i> between compartments.	CC.1.10, CC.2.2	
A.7.2	Describe the <i>equilibrium potential</i> for an ion [Nernst equation].	CC.2.2	
A.7.3	List typical equilibrium potentials for K ⁺ and Na ⁺ and explain why they differ.	CC.2.2	
A.7.4	Define <i>resting membrane potential</i> (RMP) of a cell, explain how RMP is measured, and give a typical value for RMP.	CC.2.2	
A.7.5	Describe the physiological basis of a cell's resting membrane potential (RMP), including membrane permeability to ions, types of ion channels responsible for the RMP, and the electrochemical gradients for key ions.	CC.2.2	
A.7.6	Define <i>depolarization</i> , <i>hyperpolarization</i> and <i>repolarization</i> .		
A.7.7	Given an increase or decrease in the cell's membrane permeability to K ⁺ or Na ⁺ , predict how the cell's membrane potential would change.	CC.2.2	PS-4
A.7.8	Interpret graphs showing changes in membrane potential over time.		QR-5
A.7.9	Compare the change in resting membrane potential caused by a 5 mM increase in extracellular [K ⁺] with the change caused by a 5 mM increase in extracellular [Na ⁺].		
A.7.10	Describe the role of the sodium-potassium pump (Na-K-ATPase) in maintenance of the resting membrane potential (RMP).	CC.4.1, CC.4.2 CC.4.7	
A.7.11*	Calculate the equilibrium potential for an ion species given the Nernst equation and the ECF and ICF concentrations of that ion species.	CC.2.2	QR-2
A.7.12*	Predict how altering the intracellular or extracellular concentration of an ion species would affect the equilibrium potential for that ion species, given the Nernst equation.	CC.4.6	PS-4

A.7.13*	Predict the direction an ion species will move when the cell's membrane potential is at the ion species' equilibrium potential, is less negative than the equilibrium potential, or is more negative than the equilibrium potential.	CC.2.2	PS-4
A.7.14*	Predict how the membrane potential would change, given a change in the equilibrium potential or the intracellular/extracellular concentrations of K ⁺ or Na ⁺ .	CC.2.2 CC.3.1, CC.3.3	PS-4
A.7.15*	Diagram or describe the steps that link increased blood glucose to a change in membrane potential and subsequent release of insulin from pancreatic beta cells.	CC.5.3, CC.5.4	MS-3

MODULE A Cell Physiology & Membrane Processes

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

EC-1 Atoms and molecules (EC.1.2, EC.1.4)

EC-2 Biological energy (EC.2.1-EC.2.3, EC.2.5, EC.2.6)

EC-3 Chemical bonds and reactions (EC.3.5, EC.3.7-EC.3.9)

EC-4 Organic compounds (EC.4.2, E.4.5, EC.4.6)

EC-5 Biological reactions (EC.5.2, EC.5.4, EC.5.6)

EC-6 Solutions and solubility (EC.6.1-EC.6.4)

EC-7 General organization of a cell (EC.7.1- EC.7.3)

EC-8 Cellular membrane structure and function (EC.8.1-EC.8.3)

Related LOs covered in other modules. *These are LOs that instructors might expect to see in this module but that we chose to include elsewhere.*

Module P-6 Integrated Function

P-6 Integrated physiological functions (P.6.8)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in B.1.7*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO B Cell-Cell Communication & Control Systems

Module B Cell-Cell Communication & Control Systems is a continuation of the core competencies in Module CC. It includes concepts related to cellular communication and control systems that will appear in and be referenced in most subsequent system modules.

Prior to beginning this module, students should have an understanding of:

- Cell membranes, movement across membranes, and body compartments in Module A *Cell Physiology & Membrane Processes*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.6)

Compartmentation (CC.1.9)

Mass and energy balance (CC.1.14, CC.1.16)

Molecular structure and function (CC.1.17-CC.1.22)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.8, CC.2.10)

CC-5 Communication (CC.5.2, CC.5.4)**CC-6 Systems Integration** (CC.6.2, CC.6.3)**SKILLS** addressed in this module:**Process of Science (PS)****PS-1** Draw conclusions based on inference and evidence-based reasoning. (B.2.16)**PS-4** Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (B.2.3)**Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)****MS-3** Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (B.1.5, B.2.13, B.2.16)**MS-4** Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (B.2.7)**PLO B Cell-Cell Communication & Control Systems**

At the end of an introductory one-semester physiology course, a student should be able to do the following:

Core Concepts**Skills****B-1 Cell-to-cell Communication**

B.1.1	Compare and contrast modes of local signaling and communication (e.g., <i>paracrine</i> , <i>autocrine</i> , and <i>juxtacrine signals</i> ; <i>contact-dependent signaling</i> ; <i>gap junctions</i>).	CC.5.1, CC.5.2 CC.5.3, CC.5.4	
B.1.2	Compare and contrast local (e.g., <i>paracrine</i> , <i>autocrine</i>) control mechanisms to <i>long-distance control systems</i> (e.g., <i>endocrine</i> , <i>neural</i> , <i>cytokine signaling</i>) in terms of specificity and distance/relation to target.	CC.5.1, CC.5.2 CC.5.3, CC.5.4	
B.1.3	Compare and contrast the use of chemical signals and electrical signals in control pathways (e.g., <i>local</i> , <i>endocrine</i> , <i>neural</i>) in terms of mechanism/mode of information transfer and specificity.	CC.5.1, CC.5.2 CC.5.3, CC.5.4	
B.1.4	Define <i>tonic control</i> and <i>antagonistic control</i> and list examples of each.	CC.1.6	

B.1.5	Diagram or describe the relationships among components of a reflex control pathway: <i>sensor/receptor, afferent pathway, control/integrating center, efferent pathway, target/effector</i> , and responses across levels of organization (e.g., cellular, tissue, organ system, or systemic).	CC.2.8 CC.5.4	MS-3
B.1.6	Compare and contrast <i>neural control</i> and <i>endocrine control</i> for body functions, including the anatomical pathways for signaling, targets, speed of the target response(s), duration of the response, and coding of signal intensity.	CC.6.2 CC.6.3	
B.1.7*	Compare and contrast local mediators, hormones and <i>neurocrine secretions (neurohormones, neurotransmitters and neuromodulators)</i> in terms of the cell type that releases each chemical and their general function.		
B.1.8*	Compare and contrast simple and complex neural, endocrine, and <i>neuroendocrine</i> reflex pathways in terms of the number of integrating centers and the types of signals used.	CC.2.8	
B-2 Chemical Signaling Pathways			
B.2.1	Compare and contrast the cellular signaling pathways for hydrophilic (lipophobic) signal molecules that cannot enter the cell and hydrophobic (lipophilic) signal molecules that are able to enter the cell, including the receptor location, and the speed, type, and duration of the response (e.g., changes in gene expression or temporary changes in protein activity).	CC.1.9 CC.1.18 CC.5.3	
B.2.2	Describe the relationships among ligands, receptors, and target cells.	CC.1.18	
B.2.3	Predict how changes in <i>binding affinity, specificity, competition</i> , and <i>saturation</i> affect cell signaling and communication.	CC.1.20, CC.1.21 CC.1.22	PS-1
B.2.4	Explain how receptor binding affinity and specificity determine responses to competing ligands at the cellular level (e.g., acetylcholine and nicotine; or estradiol, estrone, and estriol).	CC.1.17 CC.1.18	
B.2.5	Define the concept of <i>half-life</i> of a signal, describe methods by which chemical signaling can be terminated (e.g., enzymatic degradation, reuptake), and explain why signal termination is important.	CC.1.14	
B.2.6	Explain how one chemical signal (ligand) can have different effects across a range of target cells.	CC.1.18, CC.1.19 CC.6.2	
B.2.7	Create or interpret figures, graphs, and other visual representations of cellular signaling pathways, affinity, specificity, competition, and saturation.	CC.1.18, CC.1.19 CC.1.20 CC.1.21 CC.1.22	MS-4

B.2.8	Explain the concept of <i>signal transduction</i> as it applies to chemical signaling in the body.	CC.5.2	
B.2.9	List cellular responses that can result from activation of signal transduction pathways (e.g., electrical signals, exocytosis, calcium release, altered or new proteins, changes in enzyme activity or gene expression, movement).	CC.4.7 CC.5.2	
B.2.10	Compare and contrast membrane receptor agonists and antagonists.	CC.1.6	
B.2.11	Define <i>second messenger</i> , <i>amplifier enzyme</i> , and <i>signal amplification</i> and list some examples.		
B.2.12*	Compare and contrast the mechanisms of action, speed, and signal transduction pathways of the three major types of cell membrane receptors (e.g., G-protein coupled receptors, catalytic receptors (receptor-enzyme and integrin), and receptor-channels).	CC.5.2	
B.2.13*	Diagram or describe the signal transduction pathways mediated by major second messengers (e.g., cAMP, cGMP, inositol trisphosphate [IP ₃], diacylglycerol [DAG]), or catalytic receptors [e.g., tyrosine kinase]	CC.5.2	MS-3
B.2.14*	Describe the function and explain the purpose of phosphorylation and dephosphorylation in cell signaling, then differentiate protein kinase from protein phosphatase.	CC.1.16 CC.1.17 CC.2.8	
B.2.15	Describe the processes of activation/inactivation, up-regulation/down-regulation, and sensitization/desensitization in relation to signal molecules, their receptors, and the responsiveness of the target cell.	CC.2.10	
B.2.16	Predict how changes in activation/inactivation, up-regulation/down-regulation, or sensitization/desensitization influence cell responses.	CC.2.10	PS-1
B-3 Local Chemical Signal Molecules			
B.3.1*	Describe the major lipid paracrine signal molecules (e.g., leukotrienes and prostanoids) and their functions.		
B.3.2*	Describe the major functions of nitric oxide (NO) and the significance of its half-life.		

MODULE B Cell-Cell Communication & Control Systems

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

EC-3 Chemical bonds and reactions (EC.3.2, EC.3.4)

EC-5 Biological reactions (EC.5.5, EC.5.6, EC.5.8, EC.5.9)

EC-6 Solutions and solubility (EC.6.3, EC.6.4)

EC-7 General organization of a cell (EC.7.1)

EC-8 Cellular membrane structure and function (EC.8.1, EC.8.2)

Module A Cell physiology

A-1 Cell membrane structure and function (A.1.1)

A-2 Movement of materials across cell membranes (A.2.1, A.2.5, A.2.6, A.2.10, A.2.11)

A-3 Body fluid compartments (A.3.1, A.3.2)

A-7 Membrane potential differences (A.7.1, A.7.5, A.7.7)

Related LOs covered in other modules.

Module C *Endocrine* and Module D *Cellular Neurophysiology* contain more in-depth Learning Outcomes related to endocrine and neural signaling mechanisms and control pathways.

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in C.1.12*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO C Endocrine Physiology

Module C Endocrine Physiology begins with basic principles of endocrinology, expanding on core concepts introduced in Module B *Cell-Cell Communication & Control Systems*. Specific hormones covered in detail in this module include the hypothalamus/pituitary gland, thyroid hormones, growth and growth hormones, calcium and phosphate homeostasis, and the adrenal glands.

Many hormones with specific functions in other body systems are covered in subsequent modules.

- Blood cytokines and hormonal regulation of erythrocyte, leukocyte, and platelet production are in Module H *Blood*.
- Vasopressin/antidiuretic hormone, angiotensin, aldosterone and natriuretic peptides are in Module K *Fluid-Electrolyte & Acid-Base Balance*.
- Digestive hormones regulating the phases of digestion are in Module L *Digestive Physiology*.
- Glucagon, insulin and somatostatin are in Module M *Metabolism*.
- Sex hormones are discussed in Module N *Reproduction*, along with hormones of pregnancy and lactation.
- Stress hormones are in Module P *Integrated Function*.

Prior to beginning this module, students should have an understanding of:

- movement of material across cell membranes in Module A *Cell Physiology & Membrane Processes*

- basic cell signaling and receptor-ligand interactions in Module B *Cell-Cell Communication & Control Systems*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC: Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.2, CC.1.3, CC.1.5- CC.1.7)

Compartmentation (CC.1.9-CC.1.11)

Mass and energy balance (CC.1.13, CC.1.14)

Molecular structure and function (CC.1.15, CC.1.17, CC.1.18)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.1, CC.2.3, CC.2.4, CC.2.6, CC.2.7)

Control pathways (CC.2.8-CC.2.12)

CC-4 Energy Types, Storage, Use and Conversion (CC.4.7)

CC-5 Communication (CC.5.2)

CC-6 Systems Integration (CC.6.1, CC.6.3, CC.6.4, CC.6.5, CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (C.1.9, C.1.16, C.5.29,)

PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (C.1.6, C.1.12, C.3.10, C.4.6, C.5.16, C.5.17, C.5.20, C.6.12, C.6.13, C.6.20)

Quantitative Reasoning (QR)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (C.1.8)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (C.1.10, C.3.12, C.3.13)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (C.1.18, C.3.5, C.3.6, C.4.1, C.4.3, C.5.4, C.5.14, C.5.18, C.6.8, C.6.9)

PLO C Endocrinology			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
C-1 General Principles of Endocrinology			
C.1.1	Describe the major functions of the endocrine system.	CC.1.2	
C.1.2	Define the terms <i>hormone</i> , <i>endocrine gland</i> , <i>endocrine tissue</i> , <i>endocrine cell</i> , and <i>target cell/tissue/organ (effector)</i> .	CC.1.5	
C.1.3	Differentiate between hormones and neurohormones in terms of their sites of synthesis and release and list examples of each.	CC.1.3	
C.1.4	Apply the principle of mass balance to explain the effects of rate of secretion and clearance on the concentration of a hormone in blood plasma.	CC.1.14	
C.1.5	Describe the most common temporal patterns of hormone secretion (e.g., pulsatile, circadian, diurnal, and menstrual) and explain their significance.	CC.2.7	
C.1.6	Explain the importance of terminating hormone signaling and predict the effects on a target cell if high hormone concentrations are maintained over time (chronically).	CC.2.8 CC.2.9	PS-4
C.1.7	Explain how hypersecretion or hyposecretion of a hormone or abnormal target responsiveness (e.g., altered receptor function, signal transduction pathways) may affect cell responses to hormones.	CC.2.10 CC.5.2 CC.6.5	
C.1.8	Apply knowledge of common hormone interactions (e.g., synergism, permissiveness, antagonism) to interpret graphs or descriptions of hormone interactions.	CC.1.6, CC.1.17 CC.1.18	QR-5
C.1.9	Given the interactions of several hormones, predict the expected response of a particular target cell in the presence or absence of those hormones (e.g., thyroid hormone is permissive for growth hormone).	CC.1.17 CC.2.10 CC.6.6	PS-1
C.1.10	Given a change in a factor or situation (e.g., lack of iodine in the diet), predict the changes that may occur in an endocrine pathway and its targets.	CC.2.10 CC.6.6	MS-3

C.1.11*	Apply knowledge of negative feedback loops to examples of hormone hypersecretion, hyposecretion or abnormal target responsiveness, and predict whether each pathology would be classified as primary, secondary, or tertiary.	CC.2.9 CC.2.11	
C.1.12*	Predict how application of drugs that are hormone receptor agonists or antagonists will alter the function of an endocrine control system (e.g., the effect of exogenous cortisol on the hypothalamic-pituitary-adrenal [HPA] pathway).	CC.1.6 CC.2.10	PS-4
Chemical classification of hormones and mechanisms of hormone action at receptors			
C.1.13	Compare and contrast the three main chemical classes of hormones (peptide/protein, amino-acid-derived/amine, and steroid) in terms of synthesis, storage, release, transport in the blood, cellular location of receptor, mechanism of action (onset, type and duration), and half-life.	CC.1.17 CC.1.18	
C.1.14	Describe the influence of plasma hormone binding proteins on the amount of biologically active hormone available for receptor interactions.	CC.1.14	
C.1.15	Describe the advantages for hormone transport via plasma binding proteins (e.g., limit degradation or renal excretion, creates a hormone reservoir to maintain bioavailability).	CC.1.14	
C.1.16	Predict the chemical class of an unknown hormone from knowledge of its characteristics (e.g., synthesis, transport in the blood, half-life, mechanism of action, etc.)	CC.1.14 CC.1.17	PS-1
Control of hormone secretion			
C.1.17	For a given endocrine control system, identify the stimulus, sensor, afferent pathway, integrating/control center, efferent pathway, effector, and physiological response.	CC.2.8	
C.1.18	Diagram or describe the organization of a simple endocrine pathway (e.g., parathyroid hormone, insulin) and explain how negative feedback is used to maintain homeostasis of a regulated variable.	CC.2.8	MS-4
C.1.19	Compare and contrast the organization of a simple endocrine/neuroendocrine pathway (e.g., parathyroid hormone, insulin) with that of a complex endocrine/neuroendocrine pathway (e.g., hypothalamic-hypophyseal pathways).	CC.2.8 CC.2.9	

C-2 Hypothalamus and Pituitary Gland			
C.2.1	Compare and contrast the locations, cell and tissue types, and the anatomical relationships between the hypothalamus, anterior pituitary (adenohypophysis), and posterior pituitary (neurohypophysis).	CC.1.3	
C.2.2*	Compare and contrast the embryological development of the anterior and posterior pituitary glands.	CC.1.3	
C.2.3	List the two neurohormones released from the posterior pituitary and identify their primary targets and effects.		
C.2.4	Explain the role of the hypothalamus in the synthesis, storage, and release of neurohormones from the posterior pituitary.	CC.1.9 CC.1.11	
C.2.5	List the six primary hormones secreted by the anterior pituitary, describe their control pathways, their primary target(s) and their effects.	CC.2.8, CC.2.9 CC.2.12	
C.2.6	Explain the role of hypothalamic neurohormones in the release of anterior pituitary hormones and list the hypothalamic releasing/inhibiting neurohormone(s) for each anterior pituitary hormone.	CC.1.6 CC.2.8	
C.2.7	Describe the role of the hypothalamic-hypophyseal portal system in communication between the hypothalamus and anterior pituitary.	CC.1.9 CC.1.11	
C.2.8	Explain short-loop and long-loop negative feedback control of hypothalamic and/or anterior pituitary hormone secretion and list an example.	CC.2.9	
C-3 Thyroid Hormones			
C.3.1	Describe the location of the thyroid gland and its gross and histological anatomy.	CC.1.5	
C.3.2	Describe the structure of the thyroid follicle and the significance of the follicular cells and colloid.	CC.1.5 CC.1.9	

C.3.3	Describe the biosynthesis and processing of thyroid hormones (T ₃ and T ₄) in the thyroid gland.	CC.1.15	
C.3.4*	Compare and contrast the membrane transport of iodine, thyroid hormones (T ₃ and T ₄), and thyroglobulin by follicular cells.	CC.1.9 CC.1.13	
C.3.5	Diagram or describe the hypothalamic-hypophyseal control of thyroid hormone secretion by thyrotropin releasing hormone (TRH) and thyroid-stimulating hormone (TSH or thyrotropin).	CC.2.8 CC.2.12	MS-4
C.3.6	Diagram or describe the long-loop and short-loop feedback regulation of secretion of thyrotropin releasing hormone (TRH) and thyroid-stimulating hormone (TSH or thyrotropin).	CC.2.9 CC.2.12	MS-4
C.3.7	Explain the role and importance of thyroid-binding globulin (TBG) in thyroid hormone transport in the blood.	CC.1.14 CC.1.17	
C.3.8	Describe the role and explain the significance of tissue enzymes (deiodinases) in the transformation of T ₄ (thyroxine) to T ₃ (triiodothyronine).	CC.1.9 CC.1.17	
C.3.9	Describe the targets, target response, mechanisms of action, and physiological effects of thyroid hormones (T ₃ and T ₄).	CC.1.18 CC.2.8	
C.3.10	Predict the physiological effects of hypersecretion or hyposecretion of thyroid hormones.	CC.2.10	PS-4
C.3.11	Apply knowledge of feedback loops and the thyroid control pathway to explain how low thyroid hormone production from lack of iodine can cause enlargement of the thyroid gland.	CC.2.9 CC.2.10	
C.3.12	Applying knowledge of feedback loops, predict the effect of exogenous thyroid hormone administration on secretion of hormones in the thyroid control pathway.	CC.2.9 CC.2.10	MS-3
C.3.13	Applying knowledge of feedback loops, predict the effect of Graves disease thyroid-stimulating immunoglobulin (TSI; which mimics TSH), on secretion of hormones in the thyroid control pathway.	CC.2.9 CC.2.10	MS-3
C-4 Growth and Growth Hormones			

C.4.1	Diagram or describe the control of secretion of growth hormone (GH) by growth hormone releasing hormone (GHRH) and somatostatin (SS; also called growth hormone inhibiting hormone or GHIH).	CC.1.6 CC.2.8 CC.2.12	MS-4
C.4.2	Describe the role of growth hormone (GH) in the secretion of insulin-like growth factors (IGFs).	CC.2.8	
C.4.3	Diagram or describe the long-loop and short-loop feedback control of growth hormone secretion by growth hormone and insulin-like growth factors (IGFs).	CC.2.8 CC.2.12	MS-4
C.4.4	Describe the targets, mechanisms of action, and physiological effects of growth hormone (GH) and insulin-like growth factors (IGFs).	CC.2.8 CC.2.12	
C.4.5	Describe the importance and interactions of at least three hormones (e.g., thyroid hormone) and three other factors (e.g., diet, absence of stress, genetics) that are required for adequate growth in children.	CC.6.1, CC.6.4 CC.6.5	
C.4.6	Predict the consequences of hypersecretion and hyposecretion of growth hormone (GH) across the lifespan.	CC.2.10	PS-4
C-5 Calcium/phosphate Homeostasis and Bone			
	Calcium homeostasis		
C.5.1	List the major functions of calcium in the body.		
C.5.2	Compare and contrast calcium distribution among the cells, the extracellular fluid compartment, and bone, including the relative concentrations or amounts in each.	CC.1.9, CC.1.10 CC.1.11	
C.5.3	Describe the routes of calcium intake and loss from the body.	CC.1.11 CC.1.14	
C.5.4*	Diagram or describe the epithelial transport mechanisms for intestinal absorption of calcium, and renal reabsorption of calcium.	CC.1.11 CC.4.7	MS-4

C.5.5	Explain the importance of maintaining plasma calcium homeostasis, and list examples of dysfunction that occur when plasma calcium levels are outside a healthy range.	CC.2.1, CC.2.3 CC.2.4	
C.5.6	Explain the role of skeletal bone mass in plasma calcium homeostasis.	CC.2.1, CC.2.6 CC.6.3	
	Phosphate homeostasis		
C.5.7	Describe phosphate distribution in the body, and routes of phosphate intake and loss.	CC.1.9, CC.1.11 CC.1.14	
C.5.8	Explain the role of bone mass in plasma phosphate homeostasis.	CC.2.1, CC.2.6 CC.6.3	
C.5.9	Explain the significance of the calcium:phosphate ratio and relate it to the importance of phosphate homeostasis.	CC.2.6	
	Parathyroid hormone		
C.5.10	Describe the location and structure of the parathyroid glands.	CC.1.5	
C.5.11	Describe the synthesis, storage, release, and plasma transport of parathyroid hormone (PTH).	CC.1.15 CC.1.17	
C.5.12	List the targets for parathyroid hormone (PTH) and describe the effect(s) of PTH on each target (e.g., intestinal absorption and renal excretion of calcium and phosphate, bone resorption, calcitriol synthesis).		
C.5.13	Describe the effect of parathyroid hormone (PTH) on phosphate homeostasis.	CC.2.1	
C.5.14	Diagram or describe the regulation of parathyroid hormone (PTH) secretion and the role of negative feedback.	CC.2.8 CC.2.9	MS-4
C.5.15*	Describe the role of the calcium-sensing receptor (CaSR) in PTH secretion.	CC.2.8	
C.5.16	Predict the physiological effects of hypersecretion or hyposecretion of parathyroid hormone (PTH).	CC.2.10	PS-1

C.5.17	Apply knowledge of parathyroid mechanisms of action to predict the physiological effects of exogenous parathyroid hormone (PTH).	CC.2.10 CC.6.6	PS-1
	Calcitriol		
C.5.18	Diagram or describe steps in the processes of modification of vitamin C to biologically active calcitriol (vitamin D ₃ ; 1,25(OH) ₂ D ₃ ; 1,25 dihydroxycholecalciferol) and the location each step occurs.	CC.1.17	MS-4
C.5.19	List the targets of calcitriol and describe the actions of calcitriol on each target.		
C.5.20	Predict the physiological effects of vitamin C deficiency.	CC.2.10	PS-1
	Calcitonin		
C.5.21	List stimuli promoting secretion of calcitonin, calcitonin's effects, and identify which effects (if any) are physiologically important in humans.		
C.5.22*	Explain the relationship between calcitonin and calcitonin gene-related peptide (CGRP) and describe the biological activity of CGRP.	CC.1.17	
	Bone and bone growth		
C.5.23	List and describe the cellular and extracellular components of bone tissue.		
C.5.24	Compare and contrast the structure, function, and location of compact and spongy bone.		
C.5.25	Compare and contrast the functions of osteoblasts and osteoclasts in bone growth, repair, and remodeling.	CC.1.6	
C.5.26	Describe the process by which osteoclasts carry out bone resorption.	CC.1.14	
C.5.27	Describe the hormonal regulation of bone growth.	CC.2.8	
C.5.28*	Compare and contrast the control of osteoblast and osteoclast function during bone growth, repair, and remodeling (e.g., RANK, RANK-L, osteoprotegerin).	CC.1.6	

C.5.29	Predict the physiological effects of an imbalance in osteoclast and osteoblast activity.	CC.2.10	PS-1
C-6 Adrenal Glands			
C.6.1	Describe the gross structure of the adrenal (suprarenal) glands.	CC.1.5	
C.6.2*	Describe, compare and contrast the embryological origins of the adrenal medulla and adrenal cortex.	CC.1.3	
C.6.3	Describe, compare and contrast the control pathways for release of adrenal glucocorticosteroids and adrenal catecholamines.	CC.2.8, CC.2.9 CC.2.12	
Adrenal cortex			
C.6.4	Describe the microscopic anatomy (histology) of the adrenal cortex, and list the major hormones secreted by each zone.	CC.1.10	
C.6.5	Explain the role of cholesterol in the biosynthesis of the three classes of adrenal steroid hormones (glucocorticoids, mineralocorticoids, and androgens).	CC.1.15	
C.6.6	Describe the storage, secretion, and plasma transport of adrenal steroid hormones.	CC.1.17	
C.6.7	Describe the location of adrenal steroid hormone receptors at the cellular level and explain the general receptor mechanism of action.	CC.1.9 CC.2.8	
C.6.8	Diagram or describe the hypothalamic-hypophyseal control of cortisol secretion by corticotropin releasing hormone (CRH) and adrenocorticotrophic hormone (ACTH or corticotropin).	CC.2.8 CC.2.12	MS-4
C.6.9	Diagram or describe the long-loop and short-loop feedback regulation of corticotropin releasing hormone (CRH) and adrenocorticotrophic hormone (ACTH or corticotropin) secretion.	CC.2.8 CC.2.12	MS-4
C.6.10*	Describe the circadian rhythm of cortisol secretion and list factors that can alter the rhythm.	CC.2.7	
C.6.11	Describe the primary targets of cortisol and the major physiological actions at each target.		

C.6.12	Predict the physiological effects of hypersecretion and hyposecretion of glucocorticoids.	CC.2.10	PS-4
C.6.13	Apply knowledge of the physiological effects of glucocorticoids to predict the consequences of exogenous glucocorticoid administration.	CC.2.10 CC.6.6	PS-4
C.6.14	List the primary mineralocorticoid and its target.		
C.6.15	List the major androgens released by the adrenal cortex and their targets.		
	Adrenal medulla		
C.6.16	Describe the chemical structure of catecholamines and list three examples.	CC.1.17	
C.6.17	List the key stimuli promoting adrenal catecholamine secretion.		
C.6.18*	Describe the physiological importance of adrenal catecholamines, including their major targets and the adrenergic receptor subtypes that mediate the responses.	CC.1.18	
C.6.19	Explain the mechanism by which the catecholamines epinephrine and norepinephrine produce different effects in the same tissues.	CC.1.7 CC.1.18	
C.6.20	Apply knowledge of the physiological effects of adrenal catecholamines to predict the consequences of hypersecretion or of administration of exogenous catecholamines and their agonists (e.g., epinephrine injections, asthma inhalers).	CC.1.18 CC.2.10, CC.6.6	PS-4

MODULE D Endocrine Physiology

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

- EC-3 Chemical bonds and reactions (EC.3.4, EC.3.7)
- EC-4 Organic compounds (EC.4.5, EC.4.6)
- EC-5 Biological reactions (EC.5.9, EC.5.10)
- EC-6 Solutions and solubility (EC.6.3)
- EC-7 General organization of a cell (EC.7.1)
- EC-8 Cellular membrane structure and function (EC.8.2)
- EC-9 Genes, genomes, and gene expression (EC.9.6)

Module A Cell Physiology & Membrane Processes

- A-1 Cell membrane structure and function (A.1.1)
- A-2 Movement of materials across cell membranes (A.2.1, A.2.3, A.2.6, A.2.10)
- A-3 Body Fluid Compartments (A.3.2)
- A-4 Epithelial transport (A.4.4, A.4.6)

Module B Cell-Cell Communication & Control Systems

- B-1 Cell-to-cell communication (B.1.2, B.1.5, B.1.6)
- B-2 Chemical signaling pathways (B.2.1- B.2.11, B.2.15, B.2.16)

Related LOs covered in other modules. *These are LOs that instructors might expect to see in this module but that we chose to include elsewhere.*

Module H Blood

- H-1 Composition of blood (H.1.8)
- H-2 Erythrocytes (H.2.7)
- H-3 Leukocytes (H.3.3*)
- H-4 Platelets (H.4.3*)

Module K Fluid Electrolyte & Acid Base Balance

- K-2 Water balance and vasopressin (ADH) (K.2.1-K.2.6*)
- K-5 Angiotensin and aldosterone (K.5.1-K.5.4)
- K-6 Natriuretic peptides (K.6.1, K.6.2)

Module L Digestive Physiology

- L-3 Control of digestive function (L.3.4)
- L-5 Gastric phase of digestion (L.5.11*)
- L-6 Intestinal phase of digestion (L.6.20)

Module M Metabolism

M-4 Endocrine control of metabolism (M.4.1-M.4.12)

Module N Reproduction

N-1 Overview of reproductive systems (N.1.4*, N.1.6)

N-2 Prototypical Male Reproduction (N.2.1, N.2.7-N.2.10, N.2.13)

N-3 Prototypical Female Reproduction (N.3.1, N.3.6-N.3.10, N.3.12, N.3.18, N.3.20-N.3.24)

N-4 Reproductive function across life stages (N.4.3, N.4.6)

N-7 Pregnancy and parturition (N.7.4-N.7.6, N.7.8*)

N-8 Lactation (N.8.3*, N.8.6)

Module P Integrated Function

P-3 Integrated control of stress (P.3.1-P.3.4*)

P-6 Integrated physiological functions (P.6.1, P.6.2, P.6.4, P.6.12, P.6.13*)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in D.1.12*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO D Cellular Neurophysiology

Module D Cellular Neurophysiology covers the cellular function of neurons and glial cells and synaptic communication.

Module E *Systems Neurophysiology* looks at the divisions of the nervous system and their functions.

Prior to beginning this module, students should have an understanding of:

- Movement across membranes and membrane potential in Module A *Cell Physiology & Membrane Processes*
- Signaling modalities, chemical signaling pathways, and reflexes in Module B *Cell-Cell Communication & Control Systems*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC: Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.3, CC.1.7)

Compartmentation (CC.1.8–CC.1.12)

Molecular structure and function (CC.1.16–CC.1.22)

CC-2 Homeostasis and Control Pathways

Control pathways (CC.2.9-CC.2.11)

CC-3 Gradients and Flow (CC.3.1-CC.3.5)**CC-5 Communication** (CC.5.1-CC.5.4)**CC-6 Systems Integration** (CC.6.6)**SKILLS** addressed in this module:**Process of Science (PS)****PS-1** Draw conclusions based on inference and evidence-based reasoning. (D.3.20, D.3.21, D.4.10, D.5.1, D.5.2)**PS-4** Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (D.3.13)**Quantitative Reasoning (QR)****QR-5** Create and/or interpret figures, graphs and other quantitative representations of physiological processes. (D.3.4)**Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)****MS-3** Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (D.1.2, D.1.3, D.1.6, D.3.17, D.4.4, D.4.5, D.4.7, D.4.8)**MS-4** Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (D.1.1, D.2.2, D.3.3, D.4.3)**PLO D Cellular neurophysiology**

At the end of an introductory one-semester physiology course, a student should be able to do the following:

Core Concepts**Skills****D-1 Neurons, Glial Cells and Neurotransmitters**

D.1.1	Diagram or describe the major structures of a typical neuron (e.g., cell body, dendrites, and axon) and indicate which regions receive input signals and which components transmit output signals.	CC.1.8, CC.1.9 CC.1.11, CC.1.12	MS-4
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D.1.2	Compare and contrast the three functional types of neurons (i.e., sensory neurons, interneurons [association neurons], and motor neurons) with respect to their structure, location, and function.	CC.5.1	MS-3
D.1.3	List the most common ion channels associated with neurons, their location on the cell, channel type (leak or voltage-gated, chemically [ligand-] gated, or mechanically gated), and the direction ions flow through the open channel.	CC.1.18, CC.3.1 CC.3.3	MS-3
D.1.4*	Describe the growth and development of neurons (e.g., axon guidance and targeting).		
Glial cells			
D.1.5	List and describe the six types of glial cells, their structure, major functions, and locations (i.e., central or peripheral nervous system).	CC.1.3, CC.1.9 CC.1.10	
D.1.6	Describe the structure and function of myelin.	CC.1.10	MS-3
Neurotransmitters			
D.1.7	Compare and contrast the neurotransmitters acetylcholine and norepinephrine by their chemical composition, receptor(s), and mechanisms of action.	CC.1.18 CC.1.19 CC.1.21, CC.5.2	
D.1.8*	Compare and contrast the structures and synthesis and release of the major neurotransmitters (e.g., acetylcholine, norepinephrine).	CC.1.17	
D.1.9	Define, compare and contrast <i>cholinergic</i> and <i>adrenergic receptors</i> including their neurotransmitters, receptor subtypes (e.g., alpha & beta; muscarinic & nicotinic), and general responses (i.e., excitatory or inhibitory).	CC.5.2	
D.1.10*	List examples of endogenous and exogenous substances (e.g., nicotine, atropine) that act as agonists or antagonists for adrenergic and cholinergic neurotransmitter receptors.		
D.1.11*	List at least two examples of non-adrenergic, non-cholinergic neurotransmitters and describe their functions.		
D.1.12	Provide an example demonstrating two different responses elicited by a single neurotransmitter (e.g., acetylcholine) on different target cells.	CC.5.2	
D-2 Graded Potentials			
D.2.1	Define <i>graded potential</i> and describe how one is produced.	CC.3.1, CC.3.4 CC.5.3, CC.5.4	
D.2.2	Diagram or describe the locations where graded potentials occur in a typical motor neuron.		MS-4
D.2.3	Describe the stimuli that initiate graded potentials.	CC.5.4	

D.2.4	Describe the relation between the size of a stimulus signal, the amplitude of a graded potential (strength), and signal decay distance from the stimulation.	CC.3.3, CC.3.4 CC.5.3	
D-3 Action Potentials			
D.3.1	Define <i>action potential</i> and describe how one is triggered.	CC.5.4	
D.3.2	Compare and contrast graded and action potentials (location, amplitude (strength), duration, channel types, and functions).	CC.3.4, CC.5.3	
D.3.3	Diagram or describe the locations where action potentials occur in a typical motor neuron.		MS-4
D.3.4	Given a graph of an action potential (membrane potential as a function of time), label or describe each phase, name the ions involved in each phase, and describe the direction of ion flow across the membrane.	CC.3.1, CC.3.3 CC.3.4	QR-5
D.3.5	Compare and contrast closure versus inactivation of gated ion channels.	CC.1.16	
D.3.6	Describe changes in the gating of sodium and potassium ion channels (opening, open, closed or inactivated) and the resultant changes in ion permeability that are responsible for each phase of an action potential.	CC.3.3 CC.3.4	
D.3.7	Describe the activation and inactivation gates of voltage-gated Na ⁺ channels and explain their functions during the phases of an action potential.	CC.1.16	
D.3.8*	Explain the difference between the relative and absolute refractory periods of an action potential, relating these phases to the closure and inactivation of gated ion channels.	CC.3.4	
D.3.9	Apply knowledge of positive feedback to Na ⁺ movement through voltage-gated Na ⁺ channels and explain how the positive feedback cycle is terminated.	CC.2.9	
Initiation and conduction of action potentials			
D.3.10	Define <i>axon hillock</i> , <i>trigger zone</i> (initial segment, spike-initiation zone), <i>excitability</i> , <i>threshold potential</i> .	CC.1.8	
D.3.11	Explain how summation of graded potentials can alter the amplitude (strength) of a signal arriving at the trigger zone and influence excitability of the cell.	CC.3.3, CC.5.3 CC.5.4	
D.3.12	Compare and contrast temporal and spatial summation.	CC.5.4	
D.3.13	Predict the consequence of an increase or decrease in extracellular potassium (K ⁺) concentration on the excitability of a cell.	CC.3.3	PS-4

D.3.14	Explain how voltage-gated Na ⁺ and K ⁺ channels enable the conduction (propagation) of action potentials along the length of an axon.	CC.3.1, CC.3.4 CC.3.5	
D.3.15*	Describe the role of local current (ion) flow to neighboring axonal membrane regions in the conduction (propagation) of an action potential.	CC.3.1, CC.3.3 CC.3.4	
D.3.16	Explain how refractory periods ensure the unidirectional conduction (propagation) of action potentials from hillock to axon terminal.	CC.5.1	
D.3.17	Predict the effect on an action potential of blocking current flow through axonal Na ⁺ or K ⁺ voltage-gated channels.	CC.2.10, CC.3.1 CC.3.2, CC.3.4	MS-3
D.3.18	Compare and contrast the conduction (propagation) of action potentials in myelinated versus unmyelinated axons and in small <i>versus</i> large diameter axons.	CC.3.1, CC.3.4	
D.3.19	Explain how the distribution of ion channels in myelinated and unmyelinated segments (neurofibril nodes, nodes of Ranvier) of the axon membrane contributes to saltatory conduction.	CC.3.1, CC.3.4	
D.3.20*	Predict the physiological consequences of conditions in which myelination of axons is absent or disrupted.	CC.2.10, CC.5.1	PS-1
D.3.21*	Predict how altered function of ion channels would affect the amplitude or duration of the action potential (e.g., voltage-gated Na ⁺ channels are slow to inactivate).	CC.1.16, CC.2.10	PS-1
D-4 Synapses			
D.4.1	Define <i>synapse</i> and describe the structure of a chemical synapse (e.g., cleft, pre- and postsynaptic cells).	CC.1.7	
D.4.2*	Compare and contrast electrical and chemical synapses.	CC.5.2	
D.4.3	Diagram or describe the structures and functions of the membrane and cytoplasm comprising the axon terminal in a typical motor neuron.	CC.1.8	MS-4
D.4.4	Describe the events of synaptic transmission from the action potential arrival at the axon terminal of the presynaptic cell to the effects of neurotransmitter binding on the postsynaptic cell.	CC.5.4	MS-3
D.4.5	Describe mechanisms for termination of synaptic neurotransmitter activity (e.g., reuptake, enzymatic breakdown, diffusion) and predict the consequences of a change in the process (e.g., the inhibition of acetylcholinesterase, AChE).	CC.1.19	MS-3
D.4.6*	Apply knowledge of the concepts of affinity, specificity, competition, and saturation to neurotransmitters and their receptors.	CC.1.20, CC.1.22	

D.4.7*	Describe mechanisms for modulating synaptic transmission (synaptic plasticity).		MS-3
Postsynaptic responses			
D.4.8	Define, compare and contrast <i>excitatory postsynaptic potentials</i> (EPSPs) and <i>inhibitory postsynaptic potentials</i> (IPSPs).	CC.3.1	MS-3
D.4.9*	Compare and contrast the mechanisms responsible for fast synaptic responses (e.g., ionotropic receptors) and slow synaptic responses (e.g., metabotropic receptors).	CC.1.16	
D.4.10	Predict the physiological response of postsynaptic cells when termination of neurotransmitter signaling does not occur.	CC.2.10, CC.5.1	PS-1
D.4.11	Compare and contrast the effects of excitatory and inhibitory neurotransmitters on the postsynaptic cell.	CC.3.1, CC.5.1 CC.5.2	
D-5 Application			
D.5.1*	Given a factor or situation (e.g., a demyelinating disease, disorders of synaptic transmission), predict the changes that could occur in the nervous system and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.2.10, CC.6.6	PS-1
D.5.2*	Given a disruption in the structure or function of the nervous system (e.g., decreased neurotransmitter release), predict the possible factors or situations that might have caused that disruption (i.e., given an effect, predict the possible causes).	CC.2.11, CC.6.6	PS-1

MODULE E Cellular Neurophysiology

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

- EC-1 Atoms and molecules (EC.1.4)
- EC-2 Biological energy (EC.2.1-EC.2.3)
- EC-4 Organic compounds (EC.4.6)
- EC-5 Biological reactions (EC.5.2, EC.5.8, EC.5.9)
- EC-7 General organization of a cell (EC.7.1, EC.7.2)
- EC-8 Cellular membrane structure and function (EC.8.1)

Module A Cell Physiology & Membrane Processes

- A-1 Cell membrane structure and function (A.1.1)
- A-2 Movement of materials across cell membranes (A.2.4-A.2.8, A.2.10, A.2.11)
- A-3 Body fluid compartments (A.3.2, A.3.5)
- A-7 Membrane potential differences (A.7.1- A.7.8, A.7.10)

Module B Cell-Cell Communication & Control Systems

- B-1 Cell-to-cell communication (B.1.1, B.1.2, B.1.3, B.1.6, B.1.7)
- B-2 Chemical signaling pathways (B.2.1-2.3, B.2.5-2.12, B.2.15, B.2.16)

Related LOs covered in other modules. *These are LOs that instructors might expect to see in this module but that we chose to include elsewhere.*

Module E Systems Neurophysiology

- E-4 Peripheral nervous system: efferent divisions
- E-5 Reflexes and integrated control of movement
- E-6 Peripheral nervous system: sensory division
- E-7 The eye and vision
- E-8 Olfaction and gustation
- E-9 The ear, hearing and equilibrium
- E-10 Application

Module F Muscle Physiology

- F-3 Skeletal muscle excitation-contraction coupling

Module G Cardiovascular Physiology

- G-3 Cell physiology of cardiac muscle contraction

Module L Digestive Physiology

- L-2 Functions of the digestive system

Module P Integrated Physiological Functions (P.6.5, P.6.11*)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in E.1.10*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO E Systems Neurophysiology

Module E Systems Neurophysiology builds on the foundational information contained in Module B *Cell-Cell Communication and Control Systems* and Module D *Cellular Neurophysiology*. Topics covered in this module include the functional organization of the nervous system, divisions of the nervous system, reflexes, and special senses.

Terminology

Terms in neurophysiology can have different meanings depending on the audience. Some examples include:

- use of the word *nucleus* in brain structures, as compared to the nucleus of a cell.
- variable usage of the term *ganglia* in reference to nervous system structures. In anatomy and neuroscience, *ganglia* are defined as clusters of neuron cell bodies in the peripheral nervous system, and *nuclei* are clusters of neuron cell bodies in the central nervous system. However, in medicine, use of the term *basal ganglia* instead of *basal nuclei* in the brain is still common.
- Usage of the term *motor* varies. Sometimes 'motor neuron' or *motoneuron* is used to refer to all efferent divisions of the nervous system (somatic motor and autonomic

[visceral motor])). To clarify the difference between discussion of skeletal muscle innervation and autonomic innervation, we will use the modifier “somatic motor” to indicate skeletal muscle innervation and “visceral motor” to indicate autonomic innervation.

Prior to beginning this module, students should have an understanding of:

- Cell membrane structure and function and body compartments in Module A *Cell Physiology & Membrane Processes*
- Signaling modalities, chemical signaling pathways, and reflexes in Module B *Cell-Cell Communication & Control Systems*
- cellular function of neurons and glial cells, synaptic communication in Module D *Cellular Neurophysiology*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-function relationships

Anatomy and levels of organization (CC.1.2-CC.1.4, CC.1.6, CC.1.7)

Compartmentation (CC.1.8-CC.1.11)

Molecular structure and function (CC.1.16)

CC-2 Homeostasis and control pathways

Homeostasis (CC.2.3, CC.2.7)

Control pathways (CC.2.8, CC.2.10-CC.2.12)

CC-4 Energy types, storage, use and conversion (CC.4.2)

CC-5 Communication (CC.5.1-CC.5.4)

CC-6 Systems integration (CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (E.10.2, E.10.3)

PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (E.4.6, E.6.12, E.10.1)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (E.1.5, E.1.7, E.1.8, E.5.2, E.5.3, E.5.4, E.6.7, E.6.13, E.6.14, E.7.1, E.7.2, E.7.8, E.8.2, E.9.1, E.9.5, E.9.11)

PLO E Systems Neurophysiology			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
E-1 Organization and General Properties of the Nervous System			
	Divisions of the nervous system		
E.1.1	Describe the anatomical and functional organization of the central nervous system (CNS).	CC.1.2	
E.1.2	Describe the anatomical and functional organization of the peripheral nervous system (PNS).	CC.1.2	
E.1.3	Compare and contrast the anatomical organization of the central nervous system (CNS) with that of the peripheral nervous system (PNS).		
E.1.4	Describe the location, organization, and function of the enteric nervous system and its association with the central and peripheral nervous systems.	CC.1.2	
	Functional organization of the nervous system		
E.1.5	Diagram or describe the components of the nervous system that function as a control system, including sensory receptors, afferent (sensory) pathways, integration center (e.g., central nervous system [CNS]), efferent (motor) pathways, and targets (effectors).	CC.2.8	MS-4
E.1.6	Define, compare and contrast a <i>nerve</i> versus a <i>neuron</i> , and a <i>ganglion</i> versus a <i>nucleus</i> .		
E.1.8	Define <i>innervation</i> (of a target or effector).		
E.1.7	Describe the components of a neural (neuronal) pathway or circuit, and diagram or describe a monosynaptic pathway and a polysynaptic pathway.	CC.5.1	MS-4
E.1.8	Diagram or describe neural pathways that illustrate convergence and divergence.	CC.1.7	MS-4
E.1.9	Compare a neural network to a simple neural pathway.	CC.5.1	
E.1.10*	Define <i>neural network plasticity</i> and describe an example.		
E-2 Meninges, Cerebrospinal Fluid, and Blood-brain Barrier			
E.2.1*	List the layers of the meninges and describe their anatomical and functional relationships to the brain and spinal cord.	CC.1.2, CC.1.3	
E.2.2	Describe the composition, function, and location of cerebrospinal fluid (CSF).	CC.1.8, CC.1.9 CC.1.10 CC.1.11	

E.2.3*	Describe formation and reabsorption of cerebrospinal fluid (CSF), including the structure and function of the choroid plexus.	CC.1.4, CC.1.11	
E.2.4*	Describe the components of the blood-brain barrier (BBB), including glial cells, that influence permeability and exchange between the blood and the cerebrospinal fluid (CSF).	CC.1.9 CC.1.10 CC.1.11	
E.2.5*	Explain the functional advantages of the blood-brain barrier (BBB) in most brain regions and its absence in specific regions (e.g., the vomiting centers).	CC.1.9, CC.5.1	
E.2.6*	Describe the role of astrocytes in maintaining the blood-brain barrier (BBB) and neuronal environment to facilitate neuronal metabolism.		
E-3 Central Nervous System			
E.3.1	Identify and describe the major structures and regions of the brain, and their functions (e.g., cerebrum, cerebellum, thalamus, hypothalamus, pons, medulla).	CC.1.2	
E.3.2	List the major neurotransmitters of the central nervous system (CNS) and classify them as excitatory or inhibitory (e.g., GABA is inhibitory, norepinephrine is excitatory).	CC.1.16	
E.3.3	List the major functions of the hypothalamus.	CC.1.2	
E.3.4	List the four lobes of the cerebral cortex and describe the major function(s) of each lobe (e.g., occipital lobe is associated with vision).	CC.1.2	
E.3.5*	Define the <i>cerebral nuclei</i> (basal nuclei, basal ganglia), the <i>reticular formation</i> , and the <i>limbic system</i> , and describe the major functions associated with each.	CC.1.2	
E.3.6	Label or describe a cross-sectional view of the spinal cord to show the locations and functions of major structures (e.g., spinal nerves, gray matter, white matter, dorsal root ganglion).	CC.1.2	
E.3.7*	Define <i>ascending</i> and <i>descending spinal cord tracts</i> , and describe the structure, location, and function of each.	CC.1.2	
E-4 Peripheral Nervous System: Efferent Divisions			
E.4.1	Diagram or describe the relationships among the efferent divisions of the peripheral nervous system (PNS): autonomic (visceral motor), parasympathetic, somatic motor, and sympathetic.	CC.2.8, CC.5.1	

E.4.2	Compare and contrast the autonomic and somatic motor divisions with respect to the number of neurons in the efferent pathway, presence or absence of ganglia, chemical classification of synapses at the target (cholinergic vs adrenergic), and the types of targets.	CC.1.2	
E.4.3	Compare and contrast preganglionic and postganglionic autonomic neurons in terms of locations of origin and termination, and the neurotransmitter and receptor type at the ganglionic synapse.	CC.1.2	
E.4.4	Compare and contrast the organization and functions of the parasympathetic and sympathetic divisions of the autonomic nervous system (ANS), including where they originate in the central nervous system (CNS), the locations of ganglia, neurotransmitters released at the target synapse, receptor type(s) found on targets, and target response for each receptor type.	CC.1.2	
E.4.5	List and describe an example of how the sympathetic and parasympathetic divisions coordinate to control physiological functions.	CC.1.6, CC.5.1	
E.4.6	Given a physiological state (e.g., rest, exercise), predict the relative changes in sympathetic and/or parasympathetic signaling.	CC.2.11	PS-4
E.4.7*	Explain the relationship between the catecholamine-secreting chromaffin cells of the adrenal medulla and the sympathetic nervous system.		
E.4.8	Explain how the concept of tonic activity applies to the function of the autonomic divisions.		
E-5 Reflexes and Integrated Control of Movement			
E.5.1	Compare and contrast the pathways for a monosynaptic and a polysynaptic skeletal muscle reflex and their functional significance.		
E.5.2	Diagram or describe the neural pathway for a <i>patellar tendon reflex</i> with reciprocal inhibition of the antagonistic muscle: striking the patellar tendon with a percussion hammer results in contraction of the target muscle with the simultaneous inhibition of the antagonistic muscle.	CC.2.12	MS-4
E.5.3	Diagram or describe the neural pathway of the <i>flexor (withdrawal) reflex</i> : a painful stimulus to the right hand results in a response of the target muscle.	CC.2.12	MS-4

E.5.4*	Diagram or describe the organization and function of the <i>crossed extensor reflex</i> : a painful stimulus to the sole of the right foot, thereby causing a withdrawal reflex of the right side and an ipsilateral extensor reflex to support body weight on the left side.	CC.2.12	MS-4
E.5.5*	Compare and contrast the following reflex classification pairs and provide specific examples of each reflex: intrinsic versus learned, somatic motor versus autonomic, and cranial versus spinal.	CC.5.3	
E.5.6*	Define and describe <i>central pattern generators</i> and list an example of their contribution to the production or maintenance of a rhythmic activity (e.g., breathing, walking).	CC.2.7	
E.5.7*	Describe the location, anatomy, innervation, and function of muscle spindles.	CC.5.1, CC.5.3	
E.5.8*	Describe the location, anatomy, innervation, and function of Golgi tendon organs.	CC.5.1, CC.5.3	
E-6 Peripheral Nervous System: Sensory Division			
E.6.1	Compare and contrast somatic senses and special senses in respect to their locations and the stimuli that activate them.	CC.1.2	
E.6.2	Explain the relationship between a sensory receptor and its stimulus (adequate stimulus), its threshold, and receptor potentials.	CC.2.3	
E.6.3*	Compare and contrast simple neural, complex neural, and non-neural sensory receptors, and list/describe examples of each (e.g., free nerve endings, lamellar [Pacinian] corpuscles, and hair cells).	CC.5.2, CC.5.4	
E.6.4	Describe the stimuli transduced by the major types of sensory receptors (e.g., mechanoreceptor, thermoreceptor, photoreceptor, chemoreceptor, baroreceptor, osmoreceptor, proprioceptor, and nociceptor [pain receptor]).	CC.5.2, CC.5.3 CC.5.4	
E.6.5*	Describe the receptive field of a sensory neuron and explain its functional significance in two-point touch discrimination.	CC.5.3	
E.6.6*	List examples of locations of sensory neurons with large receptive fields versus sensory neurons with small receptive fields.	CC.5.3	

E.6.7*	Diagram or describe how the organization of primary (first-order), and secondary (second-order) sensory neurons influences two-point discrimination.	CC.1.7	MS-4
E.6.8*	Describe how lateral inhibition improves spatial two-point discrimination.	CC.5.3	
E.6.9*	Explain how information is mapped from sensory receptors to the associated primary sensory regions of the cerebral cortex (e.g., somatotopy, homunculus).		
E.6.10*	Explain how the central nervous system (CNS) determines the location of a stimulus and uses labeled line coding to determine its modality.	CC.5.1 CC.5.3	
E.6.11*	Define <i>receptor adaptation</i> and explain its functional significance.	CC.5.3	
E.6.12*	Predict how a change in action potential frequency will affect neurotransmitter release and the postsynaptic response.	CC.2.10	PS-4
E.6.13*	Given a continuous stimulus, diagram or describe what happens to action potential frequency over time for rapidly adapting phasic sensory receptors and for slowly adapting tonic receptors responses.	CC.5.3	MS-4
E.6.14*	Diagram or describe the two patterns of spinal cord sensory pathways (spinothalamic & dorsal column), comparing cell body and synapse locations for the primary, secondary, and tertiary sensory neurons; identifying the location where the sensory neuron crosses to the contralateral side (decussation); and listing the sensory modalities carried by each pathway.	CC.5.3	MS-4
E.6.15*	Describe the current models for pain modulation (gate control theory) and referred pain.	CC.5.2 CC.5.3	
E-7 The Eye and Vision			
E.7.1	Diagram or describe the path of light as it passes through the eye to the retina including the major structures.	CC.1.2	MS-4
E.7.2	Diagram or describe the refraction of light as it passes through the cornea and lens.	CC.1.8	MS-4
E.7.3	Define <i>visual accommodation</i> and explain how a change in lens shape affects the refraction of light onto the retina to create the accommodation reflex needed for near vision.		
E.7.4	Define <i>myopia</i> , <i>hyperopia</i> , <i>presbyopia</i> , and <i>astigmatism</i> , and explain how each can be corrected with the use of external lenses (eyeglasses or contact lenses).		

E.7.5	Describe the structure of the human retina, including cell types, arrangement of cell layers, and the special arrangement of the fovea.	CC.1.2	
E.7.6	Compare and contrast the functions, structural properties, and locations of rods and cones.	CC.4.2	
E.7.7	Describe the basic phototransduction process, including the roles of <i>rhodopsin</i> , <i>opsin</i> , <i>retinal</i> , <i>bleaching</i> , and recovery from bleaching.	CC.5.2	
E.7.8*	Diagram or describe the neural pathway for vision from the retina of each eye through cranial nerve II to the visual cortex.	CC.1.2 CC.4.2	MS-4
E.7.9*	Describe the collateral neural pathway for the pupillary light reflex from the retina, optic nerve, midbrain regions and oculomotor nerve.	CC.5.1	
E.7.10*	Explain the topographical organization of the retina and neural pathways that enable binocular vision using both eyes.	CC.5.1	
E-8 Olfaction and Gustation (smell and taste)			
E.8.1	Describe the structure of the olfactory epithelium, including <i>olfactory cilia</i> , <i>olfactory glands</i> , <i>support cells</i> , and olfactory sensory neurons.	CC.1.2	
E.8.2*	Diagram or describe the pathway of olfaction from olfactory receptors to the olfactory cortex.	CC.1.2, CC.5.2 CC.5.4	MS-4
E.8.3	Describe the location and structure of <i>taste buds</i> , their cell types, their associated primary sensory neurons and the cranial nerves that transmit this sensory information into the CNS.	CC.1.2, CC.5.2 CC.5.4	
E.8.4	List the basic taste sensations and the stimuli that activate them.	CC.5.2, CC.5.4	
E.8.5*	Compare and contrast the transduction processes for the basic taste sensations (i.e., GPCR and gated channel receptors).	CC.5.2 CC.5.4	
E-9 The Ear, Hearing, and Equilibrium			
E.9.1	Diagram or describe the structures sound wave energy passes along or through as it moves from the environment through the outer ear and middle ear to the cochlea.	CC.1.2	MS-4
E.9.2	Describe how the energy from sound waves is transduced into action potentials within the <i>cochlea</i> , including the role of <i>hair cells</i> and the <i>tectorial membrane</i> .	CC.5.2	

E.9.3*	Describe how a cochlear hair cell converts a supra-threshold mechanical stimulus into nerve impulses in primary sensory neurons.	CC.4.2	
E.9.4*	Explain how the structure of the <i>basilar membrane</i> helps code the frequency of sound waves into <i>pitch</i> perception.	CC.5.3	
E.9.5*	Diagram or describe the pathways for hearing from the cochlear nerves to the inferior colliculus and auditory cortex.	CC.1.2	MS-4
E.9.6	Describe the functions and three-dimensional structures of the <i>semicircular canals</i> , <i>ampullae</i> , <i>sacculae</i> , and <i>utricle</i> and their association with the cochlea.	CC.1.2, CC.1.8 CC.4.2, CC.5.2	
E.9.7*	Describe the function and structure of a <i>macula</i> .	CC.1.8, CC.4.2 CC.5.2	
E.9.8	Explain how <i>otoliths</i> and the <i>otolith membrane</i> respond to linear acceleration and head position.		
E.9.9*	Describe the function and structure of a <i>crista ampullaris</i> .	CC.1.8	
E.9.10*	Explain how the endolymph and hair cells embedded in a cupula respond to angular acceleration.		
E.9.11*	Diagram or describe the pathway from vestibular hair cells to the brainstem and cerebellum.	CC.1.2	MS-4
E-10 Application			
E.10.1	Apply knowledge of spinal cord sensory pathways to predict possible consequences of disruptions along a pathway (e.g., spinal cord lesion at a particular spinal cord level).	CC.2.10 CC.6.6	PS-4
E.10.2	Given a factor or situation (e.g., inhibition of acetylcholinesterase in the neuromuscular junction), predict the changes that might occur and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.2.10 CC.6.6	PS-1
E.10.3	Given a disruption in the structure or function of the nervous system (e.g., hearing loss), predict the possible factors or situations that might have caused that disruption (i.e., given an effect, predict the possible causes).	CC.2.11	PS-1

MODULE E Systems Neurophysiology

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

- EC-1 Atoms and molecules (EC.1.2, EC.1.4)
- EC-2 Biological energy (EC.2.1-EC.2.3, EC.2.5, EC.2.6)
- EC-3 Chemical bonds and reactions (EC.3.5, EC.3.7)
- EC-4 Organic compounds (EC.4.2, E.4.5, EC.4.6)
- EC-5 Biological reactions (EC.5.2, EC.5.4, EC.5.6)
- EC-6 Solutions and solubility (EC.6.1-EC.6.4)
- EC-7 General organization of a cell (EC.7.1-EC.7.4)
- EC-8 Cellular membrane structure and function (EC.8.1, EC.8.2)

Module A Cell Physiology & Membrane Processes

- A-1 Cell membrane structure and function (A.1.1)
- A-2 Movement of materials across cell membranes (A.2.4-A.2.8, A.2.10, A.2.11)
- A-3 Body fluid compartments (A.3.2, A.3.5)
- A-7 Membrane potential differences (A.7.1- A.7.8, A.7.10)

Module B Cell-cell Communication & Control Systems

- B-1 Cell-to-cell communication (C.1.1-C.1.7)
- B-2 Chemical signaling pathways (C.2.1-2.6, C.2.8-2.11, C.2.15, C.2.16)

Module D Cellular Neurophysiology - all

Related LOs covered in other modules. *These are LOs that instructors might expect to see in this module but that we chose to include elsewhere.*

Module F Muscle Physiology

- F-4 -3 Skeletal muscle excitation-contraction coupling

Module P Integrated function

- P-1 Thermoregulation (P.1.5*)
- P-2 Exercise physiology (P.2.4, P.2.11*)
- P-3 Integrated control of stress (P.3.2, P.3.4)
- P-4 Physiology of extreme environments (P.4.4*)
- P-6 Integrated physiological functions (P.6.6, P.6.10, P.6.11*)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in F.3.4*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO F Muscle Physiology

Module F Muscle Physiology covers the basic structure and function of skeletal, cardiac, and smooth muscle. Striated muscle physiology includes the sliding filament mechanism of striated muscle contraction and excitation-contraction coupling. Skeletal muscle and smooth muscle mechanisms of contraction are detailed in this module. Module G *Cardiovascular Physiology* contains additional learning outcomes on the microscopic structure of cardiac muscle and mechanisms of cardiac muscle contraction.

Muscle tension and related concepts are covered in the mechanics section, F-4. Reflexes and integrated control of movement are discussed in Module E *Systems Neurophysiology*. Exercise is discussed in Module P *Integrative function*.

Individual skeletal muscles or muscle groups and their actions are discussed in the appropriate body system (e.g., respiratory muscles in respiratory system). Gross smooth muscle structure and function are discussed with the appropriate body systems (e.g., bronchioles in the respiratory module, bladder in the renal module, and intestines in the digestive physiology module).

Prior to beginning this module, students should have an understanding of:

- Cell membranes and body compartments in Module A *Cell Physiology & Membrane Processes*
- functional organization of the nervous system, divisions of the nervous system and reflexes in Module E Systems *Neurophysiology*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.2, CC.1.3, CC.1.6)

Compartmentation (CC.1.8, CC.1.11)

Mass and energy balance (CC.1.13)

Molecular structure and function (CC.1.16-CC.1.19)

Properties of physical systems (CC.1.23, CC.1.24, CC.1.27)

CC-2 Homeostasis and Control Pathways

Control pathways (CC.2.10, CC.2.11)

CC-4 Energy Types, Storage, Use and Conversion (CC.4.2, CC.4.5, CC.4.7)

CC-5 Communication (CC.5.1-CC.5.4)

CC-6 Systems Integration (CC.6.4- CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (F.7.1, F.7.2)

Quantitative Reasoning (QR)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (F.4.2, F.4.3, F.4.4)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (F.2.1, F.2.2, F.2.3, F.2.7, F.3.1)

PLO F Muscle Physiology			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
F-1 Muscle Anatomy and Function			
F.1.1	Describe the major functions of muscle tissue.	CC.1.3	
F.1.2	Compare the anatomy, functions, and distribution of skeletal, cardiac, and smooth muscle within the human body.	CC.1.3	
F.1.3	Compare and contrast the general microscopic characteristics of striated (skeletal, cardiac) muscles and smooth muscle.	CC.1.3	
F.1.4	Compare and contrast a muscle fascicle, a skeletal muscle fiber (myocyte, muscle cell), a myofibril, and a myofilament.	CC.1.2 CC.1.8	
F.1.5	Explain the organization, structures, and functions of the following components within a <i>skeletal muscle fiber (cell)</i> (e.g., <i>sarcolemma</i> , <i>transverse tubules (t-tubules)</i> , <i>sarcoplasmic reticulum</i> , <i>actin</i> , <i>myosin</i> , <i>titin</i> , <i>troponin</i> , <i>tropomyosin</i> , <i>sarcoplasm</i>).	CC.1.2 CC.1.8	
F.1.6	Describe the functional arrangement of skeletal muscle groupings (e.g., flexor and extensor arrangement in antagonistic pairs).	CC.1.6	
F.1.7	Describe the function of a lever in the musculoskeletal system in terms of the position of the fulcrum and effort required to move a load.	CC.1.24	
F-2 Striated Muscle Sliding Filament Mechanism			
F.2.1	Define a <i>sarcomere</i> , and diagram or describe the arrangement of thin and thick filaments and the Z-disc (Z-line) in 3 adjacent sarcomeres.	CC.1.2	MS-4
F.2.2	Diagram or describe a myosin molecule: label the head, hinge region and tail, and describe the function of each part.	CC.1.16, CC.1.17 CC.1.18	MS-4
F.2.3	Diagram or describe and label the thin filament of striated muscle: an actin chain with its associated troponin and tropomyosin proteins.	CC.1.2	MS-4
F.2.4	Describe the arrangement and composition of myofilaments in a sarcomere including <i>A-band</i> , <i>I-band</i> , <i>H-zone</i> , <i>Z-disc (Z-line)</i> , and <i>M-line</i> .	CC.1.2	

F.2.5	Compare the length of the following components in a relaxed and in a contracted striated muscle sarcomere: A-band, I-band, and H-zone.	CC.1.2	
F.2.6	Describe the sliding filament mechanism of striated muscle contraction.	CC.1.16, CC.1.24 CC.1.27, CC.4.7	
F.2.7	Diagram or describe the relationship among troponin, tropomyosin, and actin, and explain their interactions with calcium and roles in the regulation of crossbridge cycling.	CC.1.16 CC.1.17	MS-4
F.2.8	Explain the role of ATP/ADP and myosin ATPase in the contraction cycle and the rigor state.	CC.4.2 CC.4.7	
F-3 Skeletal Muscle Excitation-Contraction Coupling			
F.3.1	Diagram or describe the structure of a neuromuscular junction between a motor neuron and a skeletal muscle fiber (cell).	CC.1.2, CC.1.3 CC.6.4	MS-4
F.3.2	Describe the events involved in the contraction of a skeletal muscle fiber (cell), including events at the neuromuscular junction, excitation-contraction coupling, and contraction cycle.	CC.1.16, CC.1.17 CC.1.19, CC.5.1 CC.5.2	
F.3.3	Compare and contrast a motor endplate potential and an action potential in a skeletal muscle fiber (cell).	CC.5.1, CC.5.2 CC.5.4	
F.3.4*	Compare and contrast a motor endplate potential with dendritic postsynaptic potentials, with respect to the postsynaptic response and the likelihood of initiating an action potential.	CC.5.3	
F.3.5	Describe the sequence of events involved in skeletal muscle relaxation, including the role of Ca-ATPase (sarco/endoplasmic reticulum Ca-ATPase, SERCA) and the sarcoplasmic reticulum.	CC.1.8, CC.1.11 CC.1.13	
F-4 Mechanics of Skeletal Muscle Contraction			
F.4.1	Define the following terms: <i>muscle tension</i> (force), <i>twitch</i> , <i>muscle tone</i> , and <i>motor unit</i> .		
F.4.2	Label the <i>latent</i> , <i>contraction</i> , and <i>relaxation periods</i> of a muscle twitch graph, and describe the cellular and molecular events that occur in each period.		QR-5
F.4.3	Explain how changes in muscle length and sliding filament zone of overlap are associated with changes in muscle tension (force), as illustrated in a muscle length-tension 'curve' (graph).		QR-5

F.4.4	Interpret graphs of muscle tension (force) versus stimulus frequency to explain the physiological basis for the phenomena of summation of twitches, unfused tetanus, and complete tetanus.	CC.2.10	QR-5
F.4.5	Define, compare and contrast <i>isotonic</i> and <i>isometric</i> contractions.		
F.4.6*	Define, compare and contrast <i>concentric</i> and <i>eccentric</i> contractions.		
F.4.7*	Describe the role of series elastic elements of muscle in isometric contractions.	CC.1.23	
F.4.8	Define a <i>motor unit</i> and describe how action potential frequency and the recruitment of different size motor units are used to progressively increase muscle tension.	CC.6.5	
F.4.9	Define <i>muscular fatigue</i> and explain the factors that may contribute to skeletal muscle fatigue.		
F-5 Muscle Metabolism			
F.5.1	Explain the importance of glycogen, creatine kinase, and phosphocreatine for ATP production in striated muscles.	CC.4.5	
F.5.2	Describe the characteristics of muscle fiber types classified by speed and duration of contraction and resistance to fatigue: slow twitch oxidative (Type I), fast twitch oxidative-glycolytic (Type IIa), fast twitch glycolytic (Type IIb/IIx).	CC.4.5	
F.5.3	Apply knowledge of the difference(s) in ATP production during glycolysis and oxidative phosphorylation to compare the duration and fatigue-resistance of muscle contraction in oxidative and glycolytic muscle fiber types.	CC.4.5 CC.4.7	
F.5.4	Explain the role of myoglobin in muscle fibers.	CC.1.16	
F-6 Smooth Muscle			
F.6.1	Compare and contrast the composition and arrangement of myofilaments in smooth muscle and skeletal muscle cells.		
F.6.2	Compare and contrast the events that initiate contraction in smooth muscle and skeletal muscle.		
F.6.3	Compare the neural and chemical control of smooth muscle contraction to that of skeletal muscle.		

F.6.4	Compare the distinguishing characteristics of multi-unit and unitary (single-unit) smooth muscle.		
F.6.5*	Compare the dynamics of smooth muscle to skeletal muscle in terms of speed and duration of contraction, length-tension relationships, and energy required for development of force.		
F.6.6*	Describe the steps of smooth muscle contraction, beginning with signals that initiate contraction and including the roles of calmodulin, myosin light chain kinase (MLCK), and myosin ATPase.	CC.4.7	
F.6.7*	Explain slow wave potentials, pacemaker potentials, and pharmacomechanical coupling as initiators of smooth muscle contraction.		
F.6.8*	Compare and contrast the molecular events of smooth muscle and skeletal muscle contraction/relaxation, including the role and source(s) of Ca^{2+} and the mechanisms for its removal from the cytosol.		
F-7 Application			
F.7.1	Given a factor or situation affecting the muscle or neuromuscular junction (e.g., muscular dystrophy, myasthenia gravis, aging), predict the changes that might occur in the muscular system and the consequences of those changes (i.e., given a cause, state possible effects).	CC.2.10 CC.6.6	PS-1
F.7.2	Given a disruption in the structure or function of the muscular system or neuromuscular junction (e.g., skeletal muscle atrophy, disrupted neuromuscular junction signaling), predict possible factors or situations that might have caused that disruption (i.e., given an effect, predict possible causes).	CC.2.11, CC.6.5 CC.6.6	PS-1

MODULE F Muscle Physiology

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

EC-2 Biological energy (EC.2.1-EC.2.5)

EC-5 Biological reactions (EC.5.2-EC.5.4, EC.5.6, EC.5.8, EC.5.9)

EC-7 General organization of a cell (EC.7.1-EC.7.4)

Module A Cell Physiology & Membrane Processes

A-1 Cell membrane structure and function (A.1.1)

A-2 Movement of materials across cell membranes (A.2.1-A.2.9)

A-3 Body fluid compartments (A.3.4, A.3.5)

A-7 Membrane potential differences (A.7.1-A.7.7, A.7.10)

Module B Cell-to-cell Communication & Control Systems

B-1 Cell-to-cell communication (B.1.1-B.1.5)

B-2 Chemical signaling pathways (B.2.2-B.2.10)

Module D Cellular neurophysiology

D-3 Action Potentials (D.3.1, D.3.2)

D-4 Synapses (D.4.1-D.4.5)

Module E Systems Neurophysiology

E-5 Reflexes and Integrated control of movement (E.5.1-E.5.4)

Related LOs covered in later modules. [*These modules contain LOs that instructors might expect to see in this module but that we chose to include elsewhere.*]

Module G Cardiovascular Physiology

G-2 Gross and microscopic anatomy of the heart

G-3 Cell physiology of cardiac muscle contraction

Module M Metabolism and its Control

M-2 Metabolism and metabolic pathways

Module P Integrative function

P-1 Thermoregulation (P.1.1, P.1.3)

P-2 Exercise physiology (P.2.4, P.2.5, P.2.8*, P.2.9*, P.2.10*, P.2.11*)

P-6 Integrated physiological functions (P.6.7)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in G.3.3*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO G Cardiovascular Physiology

Module G Cardiovascular Physiology covers the physiology of the heart and blood vessels, principles of fluid mechanics, the homeostatic mechanisms of blood pressure regulation, and capillary/lymph exchange. There are learning outcomes related to cardiac muscle structure and contraction, cardiac action potentials, and autonomic control of the heart and blood pressure. Some sections introduce terminology and mathematical relationships related to pressure, flow, resistance, volume, and cross-sectional area that require many of the *Skills Summary* quantitative reasoning skills.

Blood is covered in Module H. Gas transport in the blood is covered in Module I *Respiratory Physiology*. Lymph vessels are introduced here with capillary exchange, and their additional functions are discussed in subsequent modules.

Prior to beginning this module, students should have an understanding of:

- general membrane physiology and resting membrane potential in Module A *Cell Physiology & Membrane Processes*,
- signaling and control processes in Module B *Cell-Cell Communication & Control Systems*,
- neural control processes in Module D *Cellular Neurophysiology* and Module F *Systems Neurophysiology*,
- striated muscle contraction in Module F *Muscle Physiology*.

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.2, CC.1.3, CC.1.6, CC.1.7)

Compartmentation (CC.1.9-CC.1.12)

Properties of physical systems (CC.1.23, CC.1.25-CC.1.27)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.3-CC.2.7)

Control pathways (CC.2.8-CC.2.12)

CC-3 Gradients and Flow (CC.3.1-CC.3.5)

CC-4 Energy Types, Storage, Use and Conversion (CC.4.7)

CC-5 Communication (CC.5.1, CC.5.3)

CC-6 Systems Integration (CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (G.4.10, G.8.10, G.9.10, G.10.1, G.10.2, G.10.4, G.10.5)

PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (G.3.3, G.3.14, G.4.3, G.7.18, G.7.21)

Quantitative Reasoning (QR)

QR-2 Select and use appropriate mathematical relationships to solve problems. (G.5.6, G.5.12, G.6.10, G.6.11, G.6.12, G.7.2, G.7.3, G.7.4, G.7.6, G.7.7, G.7.8, G.7.12, G.7.15, G.8.1, G.8.2, G.9.4)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (G.3.1, G.3.2, G.3.7, G.4.7, G.4.8, G.5.8, G.5.9, G.5.10, G.6.4, G.7.5, G.7.10)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (G.2.3, G.8.3, G.8.4, G.8.7, G.8.9)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (G.4.9, G.5.2, G.8.8, G.9.2)

PLO G Cardiovascular Physiology			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
G-1 General Structure and Functions of the Cardiovascular System			
G.1.1	Describe the functions of a circulatory system and list the major substances transported by the human cardiovascular system.	CC.1.2	
G.1.2	Compare and contrast the anatomical and functional organization of the cardiovascular system.		
G.1.3	Compare and contrast the systemic and pulmonary circuits (circulations) with respect to structure and function.	CC.1.10	
G.1.4	Compare and contrast the locations and functions of the major types of blood vessels (i.e., artery, arteriole, capillary, venule, vein).		
G.1.5	Relate the tissue composition of a blood vessel wall to its specific functions.	CC.1.3	
G.1.6	Trace a drop of blood from the right atrium through the cardiovascular system until it returns to the right atrium, listing all significant anatomical structures the drop of blood encounters along the way.	CC.1.7	
G.1.7	Trace a drop of blood from a capillary in the big toe to a capillary in the finger, listing all major structures it encounters along the way.	CC.1.7	
G.1.8	Compare the relative volumes of blood in systemic and pulmonary systems.	CC.1.10	
G.1.9	Compare and contrast the oxygen content of blood in systemic and pulmonary arteries and veins.	CC.1.10	
G-2 Gross and Microscopic Anatomy of the Heart			
G.2.1	Describe the basic structure and function(s) of the heart, including the heart's position within the thorax and the pericardial sac.		
G.2.2	Compare the structural differences between atria and ventricles and relate to their functions.		
G.2.3	Explain the basic functional anatomy of the atrioventricular (AV) and semilunar valves and their mechanisms of operation.	CC.1.11	MS-3
G.2.4	Starting at the venae cavae, trace the path of blood through the heart to the aorta, listing major blood vessels and heart valves the blood passes through, and indicate whether the blood is oxygen-rich or oxygen-poor in each location.	CC.1.7 CC.1.10	
G.2.5	Describe the microscopic anatomy of contractile myocardium, including the arrangement of contractile fibers and the location, structure, and function of the intercalated discs and gap junctions.	CC.1.3	
G.2.6	Compare and contrast cardiac and skeletal muscle anatomy (e.g., cell size and shape, arrangement of myofilaments).	CC.1.3	

G.2.7	Compare and contrast the location and functions of contractile and autorhythmic myocardium.	CC.1.3	
G.2.8	Explain the functional significance of wall thickness differences between left and right ventricles.		
G-3 Cell Physiology of Cardiac Muscle Contraction			
G.3.1	Diagram or describe a typical action potential in a ventricular contractile cell, labeling the axes, the four phases of the action potential (i.e., depolarization, initial repolarization, plateau, rapid repolarization), and the ionic currents that contribute to the four phases.		QR-5
G.3.2	Diagram or describe a typical pacemaker potential and action potential of an autorhythmic myocardial cell, labeling the axes, threshold, ionic currents that contribute to the different phases, and ion channels responsible for those currents.		QR-5
G.3.3*	Predict how a change in ionic currents during the pacemaker potential of an autorhythmic myocardial cell would influence the firing rate of action potentials.	CC.2.10	PS-4
G.3.4	Compare and contrast the events that initiate action potentials in myocardial autorhythmic cells, myocardial contractile cells, and skeletal muscle cells.		
G.3.5	Compare and contrast the molecular events of cardiac muscle contraction/relaxation and skeletal muscle contraction/relaxation including the role and source(s) of Ca^{2+} and the removal of calcium from the cytosol.	CC.4.7 CC.5.3	
G.3.6	Explain the role of calcium in determining the force of myocardial contraction (contractility).	CC.5.3	
G.3.7	Interpret a graph showing the relationship between a myocardial contractile cell action potential and the cell's muscle twitch and explain why myocardial contractions do not summate.		QR-5
G.3.8	Describe the advantages of a long refractory period in contractile myocardium.	CC.5.1	
G.3.9*	Explain the molecular mechanisms responsible for the long-duration action potentials and long refractory periods in a myocardial contractile cell.		
G.3.10*	Compare and contrast the durations of action potentials and refractory periods in a myocardial contractile cell and a skeletal muscle cell, then relate these properties to summation and tetanus.		
G.3.11	Compare and contrast innervation of myocardial autorhythmic and contractile cells by sympathetic and parasympathetic neurons.		

G.3.12	Compare and contrast the influence of sympathetic and parasympathetic divisions on heart rate and contractility, specifying which division is dominant at rest or with increased heart rate.	CC.1.6	
G.3.13*	Compare and contrast the neurotransmitters, membrane receptors, and ionic mechanisms by which sympathetic and parasympathetic neurons influence heart rate and contractility.	CC.1.6	
G.3.14*	Predict how chemicals that are agonists or antagonists to ion channels and membrane receptors would influence heart rate and/or contractility (e.g., beta-1 receptor blockers, calcium channel blockers).	CC.1.6 CC.2.10	PS-4
G-4 Conduction System of the Heart			
G.4.1	List the parts of the electrical conduction system of the heart in sequence, beginning at the sinoatrial (SA) node, and explain how the electrical conduction system functions.	CC.1.27	
G.4.2	Explain how electrical signaling through gap junctions allows the myocardium to operate as a coordinated unit (i.e., functional syncytium).	CC.1.27 CC.5.1	
G.4.3*	Predict the effect of closure of gap junctions on myocardial contraction (e.g., gap junctions close because of elevated intracellular Ca^{2+} in anoxia).	CC.1.27 CC.2.10	PS-4
G.4.4	Explain the functional importance of conduction through the atrioventricular (AV) node and describe factors that influence conduction velocity through the AV node.		
G.4.5	Explain the functional significance of the atrioventricular (AV) node as the usual electrical pathway between the atria and the ventricles.	CC.1.9	
The Electrocardiogram (ECG)			
G.4.6	List the waveforms and segments of a typical electrocardiogram (ECG or EKG), and explain the electrical events represented by each waveform or segment.		
G.4.7	Label or describe the waveforms, intervals, and segments on a typical electrocardiogram (ECG or EKG).		QR-5
G.4.8	Calculate heart rate from an electrocardiogram (ECG or EKG).		QR-5
G.4.9	Diagram or describe the association between electrical events on a typical electrocardiogram (ECG or EKG) and mechanical events in the myocardium during a cardiac cycle.	CC.2.7	MS-4

G.4.10*	Predict how the following scenarios will affect myocardial contraction and the electrocardiogram: electrical signals fail to conduct through the atrioventricular (AV) node; electrical signals conduct more slowly down one side of the atrioventricular (AV) bundle.	CC.2.10	PS-1
G-5 Cardiac Cycle			
G.5.1	Define <i>cardiac cycle</i> , <i>systole</i> , and <i>diastole</i> .		
G.5.2	Diagram or describe the atrial and ventricular events of the cardiac cycle, beginning with atrial and ventricular diastole.	CC.2.7	MS-4
G.5.3	Describe atrioventricular (AV) and semilunar (SL) valve position (open/closed) and the direction of blood flow during ventricular filling, isovolumic (isovolumetric) ventricular contraction, ventricular ejection, and isovolumic (isovolumetric) ventricular relaxation.	CC.3.1	
G.5.4	Describe the process of ventricular filling and explain the contribution of atrial systole to ventricular filling at resting and elevated heart rates (e.g., during exercise).	CC.3.3	
G.5.5	Define <i>end diastolic volume</i> (EDV), <i>end systolic volume</i> (ESV), <i>stroke volume</i> (SV), and <i>ejection fraction</i> (EF).		
G.5.6*	Calculate stroke volume (SV) and ejection fraction (EF) given values for end diastolic volume (EDV) and end systolic volume (ESV).		QR-2
G.5.7	Explain how pressure changes in the heart chambers and the great vessels (i.e., the major vessels associated with the heart) in each phase of the cardiac cycle create the opening and closing of atrioventricular (AV) and semilunar (SL) heart valves.	CC.3.3	
G.5.8	Diagram or describe the following functions through one cardiac cycle: the left ventricular pressure curve, left atrial pressure curve, aortic pressure curve, left ventricular volume curve, and heart sounds	CC.2.7	QR-5
G.5.9	Diagram or describe the relationships among the left atrial and ventricular pressure and volume curves, heart sounds, and the electrocardiogram during one cardiac cycle (the Wiggers diagram).	CC.1.26 CC.2.7	QR-5
G.5.10*	Graph or describe a left ventricular pressure-volume loop diagram and label the phases and events of the cardiac cycle (e.g., atrial and ventricular systole or diastole, valve movement).	CC.1.26 CC.2.7	QR-5
G.5.11	Compare and contrast pressure and volume changes of the left and right ventricles during one cardiac cycle.	CC.1.26	
G.5.12*	Given heart rate (HR), calculate the length of one cardiac cycle.		QR-2

G-6 Control of Heart Rate, Stroke Volume, and Cardiac Output			
G.6.1	List examples of chemical signaling molecules that alter heart rate (positive and negative chronotropic agents) and describe their effects.		
G.6.2	Explain the relationships among myocardial fiber length, end diastolic volume (EDV), cardiac contractility, and stroke volume (SV).		
G.6.3	Describe how changes in end diastolic volume (EDV) affect stroke volume (SV) [Frank-Starling Law of the heart], and explain the physiological mechanism responsible (i.e., the length-tension relation in the myocardium).	CC.1.27	
G.6.4*	Using a diagram [a Starling curve], predict the effect of increasing ventricular end diastolic volume (EDV) on stroke volume and label changes in myocardial contractility that alter the curve.		QR-5
G.6.5	List examples of chemical signaling molecules that alter contractility and stroke volume (positive and negative inotropic agents), then describe their effects.		
G.6.6	Define <i>venous return</i> (VR) and describe the factors that can alter venous return.		
G.6.7	Describe the functional significance of veins as a volume reservoir.	CC.1.9 CC.1.23	
G.6.8	Define <i>preload</i> and <i>afterload</i> and describe the factors that affect them.	CC.1.23	
G.6.9	Define <i>cardiac output</i> (CO) and state its units of measurement.		
G.6.10	Explain how to calculate cardiac output (CO), given stroke volume (SV) and heart rate (HR).		QR-2
G.6.11	Predict how changes in heart rate (HR) and/or stroke volume (SV) affect cardiac output (CO).	CC.6.6	QR-2
G.6.12	Predict how end diastolic volume (EDV), end systolic volume (ESV), stroke volume (SV), ejection fraction (EF), and cardiac output (CO) are affected by an increase or decrease in venous return (VR), preload, or afterload.	CC.6.6	QR-2
G.6.13	Compare and contrast the effects of sympathetic and parasympathetic control on cardiac output (CO).	CC.1.6	
G.6.14*	Explain the mechanism by which calcium channel blockers and beta-1 receptor antagonists act as negative inotropic agents.		
G.6.15*	Explain the mechanism by which cardiac glycosides such as digitalis and digoxin act as positive inotropic agents.		

G-7 Blood Flow and Blood Pressure			
G.7.1	Explain the difference between pressure and pressure gradient.	CC.3.1	
G.7.2	Write and explain an equation that relates blood flow to pressure gradient.	CC.3.1	QR-2
G.7.3	Given fluid flowing through a rigid tube, explain how length, diameter, and viscosity determine the resistance to flow [Poiseuille's law].	CC.1.25 CC.3.4	QR-2
G.7.4	Given fluid flowing through a rigid tube, describe the change in pressure on the fluid as it moves down the length of the tube.	CC.3.4	QR-2
G.7.5	Diagram or describe how blood pressure (BP) changes as blood flows from the aorta to the venae cavae.	CC.3.3 CC.3.4	QR-5
G.7.6	Write and explain an equation that relates fluid flow to the pressure gradient and resistance of the system.	CC.3.1 CC.3.3	QR-2
G.7.7	Given the relationships among pressure gradient, flow, and resistance ($\text{flow} \propto \Delta P/R$), predict how each variable is impacted as one variable changes.	CC.3.3 CC.3.4	QR-2
G.7.8	Compare and contrast blood flow (rate) and velocity of blood flow and give the units for each.	CC.3.2	QR-2
G.7.9	Explain the difference between the cross-sectional area of a single blood vessel and the total cross-sectional area of a group of blood vessels, using capillaries as the example.	CC.1.12	
G.7.10	Given the equation for calculating velocity of flow, diagram or describe the effect of increasing total cross-sectional area on velocity of blood flow.	CC.1.12 CC.3.2 CC.3.4	QR-5
G.7.11	Compare and contrast total cross-sectional area and velocity of blood flow in the systemic arteries, arterioles, capillaries, venules, and veins.	CC.1.12 CC.3.2	
G.7.12	Given the equation relating length, radius, and viscosity to resistance [Poiseuille's law], identify the primary factor determining resistance to blood flow.	CC.1.25	QR-2
G.7.13	Identify which blood vessels experience pulsatile flow (arteries, arterioles, capillaries, and/or veins) and explain why blood flow is pulsatile in some vessels and not others.	CC.3.3	
G.7.14	Define <i>systolic arterial pressure</i> and <i>diastolic arterial pressure</i> .		
G.7.15	Given systolic and diastolic arterial pressures, calculate pulse pressure and mean arterial pressure (MAP).		QR-2
G.7.16	Explain why mean arterial pressure (MAP) is not a simple average of the systolic and diastolic pressures in the artery.		

G.7.17	Define <i>arterial compliance</i> and explain its role in maintenance of arterial blood pressure (i.e., arteries serve as the pressure reservoir).	CC.1.23	
G.7.18	Predict how systolic arterial pressure, diastolic arterial pressure, and mean arterial pressure (MAP) are affected by changes in stroke volume (SV), heart rate (HR), or arterial compliance.	CC.6.6	PS-4
G.7.19	Define <i>vasoconstriction</i> and <i>vasodilation</i> .		
G.7.20	Define <i>total peripheral resistance</i> (TPR), compare the relative contributions of systemic arteries, arterioles, capillaries, and veins to TPR, and identify which vessels are the primary site of variable (controlled) resistance to flow.	CC.3.4	
G.7.21	Predict how changing the resistance of arterioles affects systemic arterial blood pressure and regulates tissue blood flow (perfusion).	CC.3.4	PS-4
G.7.22	Describe the effects of epinephrine and norepinephrine on arteriolar resistance and identify the receptor subtype(s) for each.		
G.7.23	List the major local (autocrine or paracrine) factors that affect total peripheral resistance (TPR) and describe examples of locations where local factors act to match blood flow to tissue metabolic activity (e.g., decreased skeletal muscle pH causes vasodilation during exercise).	CC.5.1	
G.7.24	Define <i>myogenic autoregulation</i> and explain its significance in the local regulation of blood flow.	CC.5.1	
G.7.25*	Explain the cellular processes responsible for myogenic autoregulation.		
G.7.26*	Describe how metabolic regulation of blood flow can be used to explain active hyperemia and reactive hyperemia.		
G.7.27	Describe the tonic control of arteriolar diameter by sympathetic neurons.		
	Blood flow in special circulations		
G.7.28	Define a <i>portal system</i> and describe the three portal systems of the human body.		
G.7.29*	Describe the unique characteristics of skin blood flow and its control.	CC.3.3	
G.7.30*	Describe the enterohepatic circulation and explain its functions.		
G.7.31*	Explain the mechanisms that help match cerebral blood flow and brain metabolism.		
G-8 Regulation of Blood Pressure			
G.8.1	Write and explain the equation relating mean arterial pressure (MAP) to <i>cardiac output</i> (CO) and <i>total peripheral resistance</i> (TPR).		QR-2

G.8.2	Predict and describe how mean arterial pressure (MAP) is affected by changes in total peripheral resistance (TPR), cardiac output (CO), heart rate (HR) and stroke volume (SV).	CC.1.26	QR-2
G.8.3	Describe the relationship between the volume of blood in the systemic arterial circulation and mean arterial pressure (MAP).	CC.1.26	MS-3
G.8.4*	Predict and explain how mean arterial pressure (MAP) is affected by changes in preload or afterload.	CC.3.5 CC.6.6	MS-3
G.8.5	Explain how sympathetic control of venous blood volume (the venous reservoir) can be used to increase mean arterial pressure (MAP).	CC.1.26	
G.8.6	Compare and contrast the effects of sympathetic and parasympathetic control on cardiac output (CO), total peripheral resistance (TPR), and mean arterial pressure (MAP).	CC.1.6 CC.3.4	
G.8.7	Predict how a change in sympathetic or parasympathetic activity will alter cardiac output (CO), total peripheral resistance (TPR), and mean arterial pressure (MAP).	CC.6.6	MS-3
G.8.8	Diagram or describe the anatomical components and steps of the baroreceptor reflex and explain how this reflex helps maintain blood pressure homeostasis when blood pressure changes.	CC.2.3, CC.2.4 CC.2.5, CC.2.8 CC.2.12	MS-4
G.8.9	Predict the baroreceptor reflex response to a decrease in arterial blood pressure occurring upon standing (orthostatic hypotension).	G.8.9 CC.6.6	MS-3
G.8.10*	Predict how atherosclerotic vascular stiffness alters baroreceptor activity and the response to changes in mean arterial pressure (MAP).	CC.1.23 CC.6.6	PS-1
G-9 Capillaries and Lymph			
G.9.1	Compare and contrast the anatomy, location, and function of the three types of capillaries (continuous, fenestrated, discontinuous [sinusoidal]).		
G.9.2	Diagram or describe the mechanism by which proteins and large molecules cross the capillary endothelium.	CC.1.11	MS-4
G.9.3	Compare and contrast osmotic pressure and oncotic (colloid osmotic) pressure of plasma.		
G.9.4	Describe how changes in oncotic pressure and hydrostatic pressure along the length of a capillary create capillary filtration and reabsorption.	CC.3.5	QR-2
G.9.5	Predict how altering pressure or resistance in pre- or post-capillary vessels affects capillary hydrostatic pressure and fluid flow across the capillary wall.	CC.3.5	
G.9.6	Describe the major functions of the lymphatic system.	CC.1.2	

G.9.7	Compare and contrast the structure of lymphatic capillaries and systemic capillaries, including the significance of the smooth muscle in the walls of the lymphatic capillaries.		
G.9.8	Explain how changes in capillary net filtration pressure (NFP) can result in edema.	CC.3.5	
G.9.9	Explain the role of the lymphatic system in preventing edema.	CC.2.6	
G.9.10*	Apply understanding of capillary filtration mechanisms to predict how edema develops in the following scenarios: venous obstruction, lymphatic obstruction, increased capillary permeability, heart failure, histamine release following tissue injury, or protein malnutrition.	CC.3.3 CC.3.4 CC.3.5	PS-1
G-10 Application			
G.10.1	Given a factor or situation (e.g., left ventricular failure), predict the changes that might occur in the cardiovascular system and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.6.6	PS-1
G.10.2*	Given a disruption in the structure or function of the cardiovascular system (e.g., pulmonary edema), predict the possible factors or situations that might have created that disruption (i.e., given an effect, predict possible causes).	CC.2.11	PS-1
G.10.3*	Describe how atherosclerosis develops and explain how it contributes to cardiovascular disease.	CC.1.23	
G.10.4*	Explain how different mutations to ion channels of the heart (channelopathies) will affect cardiac function.	CC.2.10	PS-1
G.10.5*	Using a figure of the heart during a cardiac cycle, predict when you would hear altered heart sounds in the following conditions: mitral valve not opening completely, mitral valve not closing completely, aortic valve not opening completely, and aortic valve not closing completely.		PS-1
G.10.6	Describe the use of a sphygmomanometer and stethoscope to measure peripheral blood pressure and explain the relationship between Korotkoff sounds and pulsatile and laminar flow.		

MODULE G Cardiovascular Physiology

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

- EC-2 Biological energy (EC.2.2, EC.2.5)
- EC-5 Biological reactions (EC.5.8, EC.5.9)
- EC-6 Solutions and solubility (EC.6.1)
- EC-7 General organization of a cell (all)
- EC-8 Cellular membrane structure and function (EC.8.1)

Module A Cell Physiology & Membrane Processes

- A-1 Cell membrane structure and function (A.1.1)
- A-2 Movement of materials across cell membranes (A.2.5, A.2.7)
- A-3 Body fluid compartments (A.3.1, A.3.2, A.3.4, A.3.5, A.3.6)
- A-4 Epithelial transport (A.4.3, A.4.4, A.4.6)
- A-5 Water movement across membranes (A.5.1, A.5.2)
- A-7 Membrane potential differences (A.7.1, A.7.4, A.7.5, A.7.6, A.7.7, A.7.8, A.7.10)

Module B Cell-Cell Communication & Control Systems

- B-1 Cell-to-cell communication (B.1.1, B.1.3, B.1.4, B.1.5)
- B-2 Chemical signaling pathways (B.2.2, B.2.3, B.2.4, B.2.5, B.2.6, B.2.7, B.2.8, B.2.9, B.2.10, B.2.15)
- B-3 Local chemical signal molecules (B.3.2*)

Module D Cellular Neurophysiology

- D-1 Neurons, Glial Cells and Neurotransmitters: Neurotransmitters (D.1.7, D.1.9, D.1.10*, D.1.12)
- D-3 Action Potentials (D.1.1, D.3.4, D.3.6, D.3.8*)
- D-4 Synapses (D.4.1, D.4.4, D.4.5, D.4.6)

Module E Systems Neurophysiology

- E-1 Organization and general properties of the nervous system (E.1.1, E.1.2, E.1.5, E.1.8)
- E-4 Peripheral nervous system: efferent divisions (all)
- E-6 Peripheral nervous system: sensory division (E.6.2, E.6.3, E.6.4, E.6.12*)

Module F Muscle Physiology

- F-1 Muscle anatomy and function (F.1.1- F.1.3, F.1.5)
- F-2 Striated muscle sliding filament theory (F.2.1-F.2.7)

Related LOs covered in other modules. *[These are LOs that instructors might expect to see in this module but that we chose to include elsewhere.]*

PLO H Blood

H-1 Composition of blood

H-2 Erythrocytes

PLO I Respiratory Physiology

I-1 Structure and function of the respiratory system (I.1.5, I.1.10*)

I-2 Pulmonary ventilation (I.2.6*)

I-6 Local control of ventilation and gas exchange (I.6.1)

I-7 Oxygen transport in blood (I.7.1-I.7.3)

I-8 Carbon dioxide transport in blood (I.8.2)

PLO J Renal Physiology

J-1 Anatomy of the urinary system (J.1.7, J.1.9)

J-3 Glomerular filtration (J.3.6-J.3.17)

J-6 Application (J.6.3)

Module K Fluid-Electrolyte & Acid-Base Homeostasis

K-7 Integrated control of blood volume, blood pressure and osmolarity (K.7.1-K.7.10*)

PLO L Digestive Physiology

L-6 Intestinal phase of digestion (L.6.6, L.6.10, L.6.11, L.6.28)

PLO N Reproductive Physiology

N-7 Pregnancy and parturition (N.7.3)

PLO P Integrated Function

P-1 Thermoregulation (P.1.1, P.1.5*)

P-2 Exercise physiology (P.2.2, P.2.4, P.2.5, P.2.11*)

P-4 Physiology of extreme environments *

High altitude (P.4.1*, P.4.2*)

Diving (P.4.4*)

Space (P.4.6*, P.4.7*, P.4.9*)

P-5 Integrated response to COVID (P.5.3*)

P-6 Integrated physiological functions (P.6.3, P.6.6, P.6.7)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in H.1.5*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO H Blood

Module H Blood topics include the composition of blood, erythrocytes, leukocytes, platelets, hemostasis, and blood typing. In our experience physiologists discuss blood typing with blood because many introductory physiology courses do not include the immune system. However, the inclusion of blood typing here requires the instructor to introduce the terms *antigen* and *antibody*. The learning outcomes for those terms are in Module O *Immune System*.

The functions of leukocytes are covered with immunity and inflammation in Module O *Immune System* rather than in this module. Additional learning outcomes for hemoglobin are in Module I *Respiratory Physiology*, along with oxygen and carbon dioxide transport in blood. The integrated control of blood volume, osmolarity, and acid-base homeostasis is discussed in Module K *Fluid-electrolyte & Acid-base Homeostasis*.

Terminology: Previously, erythrocytes were also called corpuscles, resulting in terminology such as mean corpuscular volume (MCV). Modern usage has simplified the language by substituting “cell” for “corpuscle,” so that MCV now also refers to “mean cell volume.” We use the modern terminology in this unit.

Prior to beginning this module, students should have an understanding of:

- membrane physiology and body compartments in Module A *Cell Physiology & Membrane Processes*
- signaling and control processes in Module B *Cell-Cell Communication & Control Systems*

- blood vessels in Module G *Cardiovascular Physiology*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.7)

Compartmentation (CC.1.8, CC.1.12)

Mass and energy balance (CC.1.13, CC.1.14)

Molecular structure and function (CC.1.16, CC.1.18, CC.1.19)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.1, CC.2.4)

Control pathways (CC.2.8-CC.2.10)

CC-5 Communication (CC.5.1, CC.5.3)

CC-6 Systems Integration (CC.6.5)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (H.2.9, H.5.9, H.6.5)

PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (H.6.4)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (H.5.3, H.5.8, H.6.3)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (H.5.4, H.5.6)

PLO H Blood			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
H-1 Composition of Blood			
H.1.1	Describe the cellular elements and extracellular matrix (plasma) of blood.	CC.1.8	
H.1.2	List the major groups of solutes dissolved in plasma (e.g., ions, gasses).		
H.1.3	List the major types of plasma proteins (e.g., albumin, globulins) and for each, describe where they are synthesized and their functions.		
H.1.4	Compare and contrast the morphological features and major functions of the three main cellular elements of blood: erythrocytes (red blood cells), leukocytes (white blood cells), and thrombocytes (platelets).		
H.1.5*	Compare the relative sizes and abundance of erythrocytes, leukocytes, and platelets in whole blood of a healthy adult.		
H.1.6	Define <i>hematocrit</i> and explain its physiological significance.		
H.1.7	Define <i>hematopoiesis</i> and compare the locations for hematopoiesis in the embryo, in children, and in adults.		
H.1.8*	Explain the role of stem cells and cytokines in hematopoiesis.		
H-2 Erythrocytes			
H.2.1	Compare the structures of reticulocytes and mature erythrocytes (red blood cells, RBCs).	CC.1.12	
H.2.2	Describe the functional consequences of the absence of a nucleus, ribosomes, and mitochondria in mature erythrocytes on protein synthesis, energy production, and lifespan.		
H.2.3	Describe the structure of hemoglobin (Hb, Hgb) and relate its structure to its functions.	CC.1.16	
H.2.4*	Describe iron homeostasis in the body, including its absorption from the diet, transport in blood, hepatic storage, recycling, and excretion.	CC.1.14 CC.2.1	
H.2.5	Describe the breakdown and recycling of aged erythrocytes (RBCs) and their components (e.g., heme).	CC.1.14	
H.2.6*	Compare and contrast erythrocyte (RBC) count, hemoglobin concentration of blood, mean cell volume (MCV), mean cell hemoglobin (MCH), and mean cell hemoglobin concentration (MCHC).		

H.2.7	Identify the site of erythropoietin (EPO) production, the stimulus for EPO release, the target tissue(s) for EPO, and the action of EPO at its target.	CC.2.8	
H.2.8*	Explain how disruption of the typical balance between erythropoiesis (erythrocyte synthesis) and erythrocyte loss can result in anemia or polycythemia.	CC.1.13 CC.2.1	
H.2.9*	Explain how erythrocyte (RBC) disorders (e.g., anemia, spherocytosis, sickle cell disease) can affect oxygen transport.	CC.2.10	PS-1
H-3 Leukocytes			
H.3.1	List the five types of leukocytes (white blood cells, WBCs) found in healthy blood, compare their relative abundance, and describe their histological appearance in a blood smear.		
H.3.2*	Given an image of a blood smear, identify the types of leukocytes based on their morphology.		
H.3.3*	Explain the role of cytokines, including colony-stimulating factors (CSFs), in leukopoiesis.		
H-4 Platelets			
H.4.1	Describe the structure, function, and location of megakaryocytes.		
H.4.2	Describe the structure and functions of platelets (thrombocytes).		
H.4.3*	Explain the role of thrombopoietin (TPO) in the process of thrombopoiesis.		
H-5 Hemostasis			
H.5.1	Define <i>hemostasis</i> and describe its three major steps (i.e., vascular spasm, platelet plug formation, and coagulation).	CC.2.4 CC.2.8	
H.5.2	Describe the process of platelet activation and the formation of a platelet plug.	CC.5.1	
H.5.3*	Compare and contrast the intrinsic (contact activation) and extrinsic (cell injury) pathways of the coagulation cascade and explain the significance of these pathways converging at the common pathway.	CC.1.7 CC.5.1	MS-3
H.5.4	Beginning with prothrombin, diagram or describe the enzymes and substrates involved in the formation of fibrin polymers.		MS-4
H.5.5	Explain the mechanisms that limit activation of the clotting cascade to the site of injury.	CC.5.1	
H.5.6	Diagram or describe the positive feedback loops in the platelet and coagulation phases and explain their significance to the process of hemostasis.	CC.2.4 CC.2.9	MS-4
H.5.7	Describe the process of fibrinolysis, including the roles of plasminogen, tissue plasminogen activator, and plasmin.		
H.5.8*	Predict the results of a change in the steps of hemostasis (e.g., decreased fibrinogen).	CC.2.10	MS-3

H.5.9*	Define <i>anticoagulant</i> , list some examples, and describe how anticoagulants may be harmful or therapeutic.	CC.2.10	PS-1
H-6 ABO and Rh Blood Groups			
H.6.1	Explain how erythrocyte surface proteins determine blood type by the ABO blood groupings and rhesus (Rh) factor classifications.	CC.5.3	
H.6.2	List the cell surface antigens and corresponding antibodies for each ABO and Rh blood type.	CC.1.18	
H.6.3	Apply your understanding of cell surface antigens and plasma antibodies to predict which blood types are compatible for transfusion, and which blood types can serve as universal donors or universal recipients.	CC.1.19	MS-3
H.6.4*	Given information about agglutination in the presence of anti-A, anti-B, or anti-Rh antibodies, predict blood type.	CC.1.19	PS-4
H.6.5*	Given the phenotype or genotype of parents, predict the possible blood types of offspring, or vice versa.		PS-1
H-7 Application			
H.7.1	Define <i>anemia</i> and explain potential causes of anemia (e.g., iron deficiency, blood loss, genetic mutations of hemoglobin).	CC.6.5	
H.7.2	Define <i>polycythemia</i> and compare and contrast <i>true polycythemia</i> (polycythemia vera) and <i>relative polycythemia</i> .		

MODULE H Blood

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

EC-4 Organic compounds (EC.4.6)

EC-6 Solutions and solubility (EC.6.1, EC.6.2, EC.6.5, EC.6.6)

EC-7 General organization of a cell (EC.7.1, EC.7.2, EC.7.4)

EC-8 Cellular membrane structure and function (EC.8.1, EC.8.3)

Module A Cell Physiology & Membrane Processes

A-1 Cell membrane structure and function (A.1.1)

A-2 Movement of materials across cell membranes (A.2.1, A.2.3, A.2.4, A.2.5, A.2.10)

A-3 Body fluid compartments (A.3.1-A.3.6)

A-5 Water movement across membranes (A.5.2, A.5.3)

A-6 Osmolarity and tonicity (A.6.2, A.6.3, A.6.7, A.6.10*)

Module B Cell-Cell Communication & Control Systems

B-1 Cell-to-cell communication (B.1.1)

B-2 Chemical signaling pathways (B.2.2, B.2.7, B.3.2*)

Module G Cardiovascular

G-1 General structure and functions of the cardiovascular system (G.1.1)

G-9 Capillaries and lymph (G.9.2, G.9.3, G.9.4)

Related LOs covered in other modules *[These are LOs that instructors might expect to see in this module but that we chose to include elsewhere]*

Module I Respiratory Physiology

I-5 Gas exchange in the lungs and tissues (I.5.3, I.5.4*)

I-7 Oxygen transport in blood (I.7.1-I.7.3, I.7.5-I.7.10*, I.7.12, I.7.13*, I.7.14*)

I-8 Carbon dioxide transport in blood (I.8.1-I.8.7)

I-10 Application (I.10.1)

Module J Renal Physiology

J-2 Functions and processes of the urinary system (J.2.7)

J-3 Glomerular function (J.3.11)

Module K Fluid-Electrolyte & Acid-Base Homeostasis

K-3 Sodium balance (K.3.3, K.3.4)

K-7 Integrated control of blood volume, blood pressure, and osmolarity (K.7.1-K.7.10*)

K-8 Acid-base homeostasis (K.8.1, K.8.5, K.8.7, K.8.8, K.8.9)

Module O Immune System

O-1 General structure and function (O.1.4)

O-2 Innate immunity and adaptive immunity (O.2.3, O.2.4*, O.2.6)

O-3 Phagocytosis and antigen presentation (O.3.1-O.3.4)

O-4 Antibody function (O.4.1-O.4.6)

Module P Integrated Functions & Special Environments

P-2 Exercise Physiology (P.2.3, P.2.4, P.2.5)

P-4 Physiology of extreme environments

High Altitude (P.4.1*, P.4.2*), Diving (P.4.5*), Space (P.4.6*, P.4.7*)

P-6 Integrated physiological functions (P.6.10)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in I.1.7*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO I Respiratory physiology

Module I Respiratory Physiology covers the physiology of the respiratory system including ventilation, breathing mechanics, pulmonary function tests, gas transport and exchange, and neural control of ventilation.

Hemoglobin and red blood cells are introduced in Module H *Blood*, section H-2 *Erythrocytes*.

Prior to beginning this module, students should have an understanding of:

- basics of epithelial transport in Module A *Cell Physiology & Membrane Processes*
- chemical signaling pathways in Module B *Cell-Cell Communication & Control Systems*
- autonomic and somatic motor control in Module E *Systems Neurophysiology*
- organization of the systemic and pulmonary circuits in Module G *Cardiovascular Physiology*
- the composition of blood in Module H *Blood*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

A-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.2-CC.1.5, CC.1.7)

Compartmentation (CC.1.8, CC.1.9, CC.1.11, CC.1.12)
 Mass and energy balance (CC.1.14)
 Molecular structure and function (CC.1.16-CC.1.22)
 Properties of physical systems (CC.1.23, CC.1.25-CC.1.27)

A-2 Homeostasis and Control Pathways

Homeostasis (CC.2.2-CC.2.8)
 Control pathways (CC.2.10-CC.2.12)

A-3 Gradients and Flow (CC.3.1-CC.3.5)

A-4 Energy Types, Storage, Use and Conversion (CC.4.3)

A-5 Communication (CC.5.1)

A-6 Systems Integration (CC.6.1, CC.6.3, CC.6.4, CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (I.1.10, I.2.16, I.4.5, I.10.1, I.10.2, I.10.3)

PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (I.2.15, I.6.4, I.6.5)

Quantitative Reasoning (QR)

QR-2 Select and use appropriate mathematical relationships to solve problems. (I.2.4, I.2.5, I.2.10, I.2.12, I.3.2, I.5.2)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (I.2.7, I.2.13, I.4.3, I.4.4, I.7.4, I.7.5, I.7.6, I.7.10, I.7.12, I.7.13, I.7.14)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (I.7.3, I.8.6, I.8.7, I.9.4)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (I.8.1, I.8.2, I.8.4, I.8.5, I.9.3)

PLO I Respiratory physiology			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
I-1 Structure and Functions of the Respiratory System			
I.1.1	Describe the major functions of the respiratory system.	CC.1.2	
I.1.2	List and describe the major steps required for the movement of atmospheric gases between the environment and the body's cells.	CC.1.8, CC.1.11 CC.1.14, CC.3.1 CC.6.1, CC.6.4	
I.1.3	List, in order, the respiratory structures that air passes through during breathing, from the mouth and nose to the exchange surface of the lungs.		
I.1.4	Explain the structural and functional relationships of the visceral and parietal pleura (pleural sacs), pleural fluid, thoracic cage, heart, and lungs.	CC.1.9	
I.1.5	Compare and contrast the systemic and pulmonary circulations with respect to blood pressures, relative blood volumes, blood flow rate, and resistance.	CC.3.4	
I.1.6	Describe the branching structure of the airways, starting at the trachea and ending at alveoli, and explain the microscopic and macroscopic anatomical differences from trachea to bronchi and bronchioles to alveoli (e.g., cartilage, smooth muscle, epithelia).	CC.1.7	
I.1.7*	Explain how ciliated epithelial cells, goblet cells, and secretory cells in submucosal glands contribute to the mucociliary escalator and the functions of the airways.	CC.1.4 CC.1.5	
I.1.8	Compare and contrast the functions of the bronchi, terminal bronchioles, respiratory bronchioles, and alveoli.	CC.1.7 CC.1.12	
I.1.9	Compare and contrast the functions of type I and type II alveolar cells (pneumocytes).	CC.1.4, CC.1.5	
I.1.10*	Apply understanding of oncotic pressure, hydrostatic pressure, and capillary filtration/reabsorption to explain why fluid does not usually accumulate in the interstitial compartment of the lungs.	CC.1.11, CC.3.1 CC.3.5	PS-1
I-2 Pulmonary Ventilation			
I.2.1	Define <i>ventilation</i> , <i>inspiration (inhalation)</i> , and <i>expiration (exhalation)</i> .		
I.2.2	List the muscles used during quiet inspiration, deep inspiration, and forced expiration.		
I.2.3	Describe the innervation of the diaphragm, including the division of the nervous system, its neurotransmitter and receptor type.		

I.2.4	Describe how changing the volume of a gas affects its pressure [Boyle's Law].	CC.1.26	QR-2
I.2.5	Apply understanding of the inverse relationship between gas pressure and volume of the gas to explain how changes in volume create airflow during inspiration and expiration.	CC.1.26 CC.3.1	QR-2
I.2.6*	Compare and contrast air flow in the respiratory system to blood flow in the cardiovascular system, including the following concepts: the pump, direction(s) of flow, properties of the fluid flowing, factors influencing resistance to flow, neural control of flow and resistance.	CC.1.25, CC.3.1 CC.3.4	
I.2.7	Graph or describe the change in intrapleural pressure, alveolar pressure, airflow, and lung volume during a normal quiet breathing cycle, identifying the onset of inspiration, cessation of inspiration, onset of expiration, cessation of expiration, and the timepoints where atmospheric pressure is equal to alveolar pressure.	CC.1.26, CC.2.7 CC.3.1, CC.3.3	QR-5
I.2.8*	Explain the forces that keep intrapleural pressure subatmospheric at the end of a quiet expiration.	CC.1.27	
I.2.9	Define <i>anatomic dead space</i> .		
I.2.10	Define <i>total pulmonary (minute) ventilation</i> and <i>alveolar ventilation</i> , and given data, calculate each.		QR-2
I.2.11	Compare and contrast alveolar ventilation and total pulmonary (minute) ventilation.		
I.2.12	Define <i>partial pressure of a gas</i> , and given data, calculate the partial pressure of a gas [Dalton's law].	CC.1.26	QR-2
I.2.13	Graph or describe the changes in alveolar P_{CO_2} and P_{O_2} that occur with increasing or decreasing alveolar ventilation.		QR-5
I.2.14	Define the following terms: <i>hypoventilation</i> , <i>hyperventilation</i> , <i>eupnea</i> , <i>dyspnea</i> , <i>apnea</i> , and <i>hyperpnea</i> .		
I.2.15	Predict the change in alveolar P_{CO_2} and P_{O_2} after two minutes of hypoventilation, hyperventilation, or rebreathing air from a paper bag.	CC.2.10	PS-4
I.2.16*	Apply understanding of anatomic dead space to explain the effect of using a snorkel or mechanical ventilation (e.g., CPAP) on alveolar ventilation.	CC.2.10	PS-1
I-3 Pulmonary Mechanics			
I.3.1	Define <i>compliance</i> and <i>elastance</i> in the context of the lung and pulmonary ventilation.	CC.1.23	
I.3.2	Explain the role of surface tension and surfactants in lung compliance [Law of Laplace].	CC.1.17	QR-2

I.3.3	Describe the effects of airway diameter on airway resistance and identify the sites of greatest resistance and of variable resistance in a healthy person.	CC.3.2	
I.3.4	List the factors influencing airway resistance.	CC.3.4	
I.3.5*	Describe two common pathological conditions in which lung compliance is higher or lower than normal and explain the physiological consequence of the change in compliance.	CC.1.23	
I.3.6	Explain the effect of bronchiolar smooth muscle contraction (bronchoconstriction) on pulmonary ventilation and list some factors that cause bronchoconstriction.	CC.3.4	
I.3.7*	Explain the effect of bronchiolar smooth muscle contraction (bronchoconstriction) on the work of breathing.	CC.3.4 CC.4.3	
I-4 Pulmonary Function Tests			
I.4.1	Define the four pulmonary volumes -- <i>inspiratory reserve volume</i> (IRV), <i>tidal volume</i> (TV), <i>expiratory reserve volume</i> (ERV), and <i>residual volume</i> (RV) -- and the four pulmonary capacities: <i>inspiratory capacity</i> (IC), <i>functional residual capacity</i> (FRC), <i>vital capacity</i> (VC), and <i>total lung capacity</i> (TLC).		
I.4.2	Identify the pulmonary volumes that make up each of the four respiratory capacities, and which volume and capacities cannot be measured by spirometry.		
I.4.3	Graph or describe a typical spirogram, indicating the four lung volumes (inspiratory reserve volume (IRV), tidal volume (TV), expiratory reserve volume (ERV), and residual volume (RV)) and four capacities (inspiratory capacity (IC), functional residual capacity (FRC), vital capacity (VC), and total lung capacity (TLC)).		QR-5
I.4.4*	Given a spirogram showing a maximal expiratory effort, label or interpret the forced vital capacity (FVC) and FEV1 (forced expiratory volume in 1 second).	CC.3.3	QR-5
I.4.5*	Compare and contrast restrictive and obstructive lung disease, explain possible causes (e.g., changes in elastance), and predict how obstructive and restrictive lung diseases alter the outcomes of pulmonary function tests, including the FEV1 (forced expiratory volume in 1 second).	CC.3.4	PS-1
I-5 Gas Exchange in the Lungs and Tissues			
I.5.1	Explain the relationship between the total pressure of gases in a mixture and the partial pressure of an individual gas [Dalton's Law].		
I.5.2	List the percentages of O ₂ and CO ₂ in air and calculate their partial pressures at sea level (760 mm Hg).		QR-2

I.5.3	Compare and contrast the relative solubilities of O ₂ and CO ₂ in plasma.		
I.5.4*	Explain how a liquid with P _{O2} of 100 mm Hg and a P _{CO2} of 100 mm Hg can have about 20x higher concentration of dissolved CO ₂ compared to dissolved O ₂ .	CC.2.2	
I.5.5	List the typical atmospheric, alveolar, arterial, and venous blood P _{O2} and P _{CO2} values, and use them to describe the gradients and direction of diffusion for O ₂ and CO ₂ in the alveolar and systemic capillaries.	CC.3.1	
I.5.6	Describe the factors that influence diffusion of a gas between alveoli and pulmonary capillary blood.	CC.1.11, CC.2.6 CC.3.1	
I.5.7	Describe the influence of cellular respiration on the O ₂ and CO ₂ gradients promoting gas exchange between systemic capillaries and body tissues.	CC.2.10	
I-6 Local Control of Ventilation and Gas Exchange			
I.6.1	Explain the effects of local changes in O ₂ and CO ₂ concentrations on the diameters of pulmonary arterioles and bronchioles.	CC.2.4	
I.6.2*	Explain how local effects of pulmonary O ₂ and CO ₂ concentrations are responsible for ventilation-perfusion matching (i.e., the V/Q ratio).	CC.2.4	
I.6.3*	Contrast the response to hypoxia in systemic and pulmonary arterioles.	CC.2.10	
I.6.4*	Apply knowledge of the mechanisms of ventilation-perfusion matching (the V/Q ratio) to predict the effect of reduced alveolar ventilation on the distribution of pulmonary blood flow.	CC.2.10	PS-4
I.6.5*	Apply knowledge of ventilation-perfusion matching (the V/Q ratio) to predict the effect of reduced pulmonary blood flow on bronchiole diameter.	CC.2.10	PS-4
I-7 Oxygen Transport in Blood			
I.7.1	Diagram or describe the methods of O ₂ transport in blood (i.e., dissolved, bound to hemoglobin), and state the percentage of total O ₂ transported by each method.	CC.1.11 CC.1.19	MS-4
I.7.2	Define <i>percent O₂ saturation of hemoglobin</i> .	CC.1.20	
I.7.3	Write the reversible chemical equation for O ₂ binding to hemoglobin (Hb) and predict how increasing or decreasing the partial pressure of O ₂ will shift the equilibrium.	CC.1.20 CC.1.21	MS-3
I.7.4	Graph or describe an oxyhemoglobin dissociation curve (O ₂ -Hb saturation curve) explaining the relationship between O ₂ partial pressure and Hb saturation.	CC.1.20	QR-5

I.7.5	Define <i>P50</i> for Hb saturation and interpret on an oxyhemoglobin dissociation curve.	CC.1.20	QR-5
I.7.6*	Given an oxyhemoglobin dissociation curve, interpret Hb saturation at a particular PO ₂ , or vice versa (e.g., given percent saturation, predict the PO ₂ of the blood).	CC.1.20 CC.1.21	QR-5
I.7.7	Explain what happens to hemoglobin's affinity for oxygen and to oxygen release at the tissues when the oxyhemoglobin saturation curve shifts to the right.	CC.1.17 CC.1.18	
I.7.8	Explain what happens to hemoglobin's affinity for oxygen and to oxygen release at the tissues when the oxyhemoglobin saturation curve shifts to the left.	CC.1.17 CC.1.18	
I.7.9	Describe how changes in blood temperature, pH, P _{CO2} , and 2,3-BPG (2,3-DPG) affect O ₂ transport.	CC.1.17 CC.1.18	
I.7.10*	Interpret a graph demonstrating a shift in an oxyhemoglobin dissociation curve to approximate the change in O ₂ release at the tissues or O ₂ bound in the lungs.		QR-5
I.7.11*	List factors that influence arterial O ₂ content (e.g., composition of inspired air, O ₂ -Hb binding sites) and predict how a change in each factor will affect arterial O ₂ .	CC.1.17, CC.1.22 CC.2.10	PS-1
I.7.12	Predict how anemia affects arterial P _{O2} , oxyhemoglobin saturation, and the shape of the oxyhemoglobin dissociation curve.	CC.1.20, CC.1.21 CC.2.10	QR-5
I.7.13*	Predict how carbon monoxide (CO) poisoning affects arterial P _{O2} , oxyhemoglobin saturation, and the shape of the oxyhemoglobin dissociation curve.	CC.1.17, CC.1.20 CC.1.21, CC.1.22 CC.2.10	QR-5
I.7.14*	Interpret the shape of the fetal oxyhemoglobin saturation curve to explain the influence of fetal Hb on O ₂ delivery to fetal tissues.	CC.1.17 CC.1.20	QR-5
I-8 Carbon Dioxide Transport in Blood			
I.8.1	Diagram or describe the reversible chemical equation for the conversion of CO ₂ and H ₂ O to hydrogen ion (H ⁺) and bicarbonate ion (HCO ₃ ⁻), then explain the role of <i>carbonic anhydrase</i> in this reaction (i.e., bicarbonate buffer system).	CC.1.16, CC.1.17 CC.2.2	MS-4
I.8.2	Diagram or describe the methods of CO ₂ transport in blood (i.e., dissolved, as bicarbonate, and as <i>carbaminohemoglobin</i> [Hb-CO ₂]), and state the percentage of total CO ₂ transported by each method.	CC.1.19	MS-4
I.8.3	Define <i>hypercapnia</i> and <i>hypocapnia</i> .		
I.8.4	Diagram or describe, in order, the steps required for CO ₂ to exit the pulmonary capillary blood and enter the alveoli.	CC.1.3, CC.1.11 CC.2.6	MS-4

I.8.5*	Diagram or describe the chloride shift in red blood cells and explain its importance in the storage and transport of CO ₂ in the blood.	CC.1.11 CC.1.19	MS-4
I.8.6	Predict how increasing or decreasing blood P _{CO2} affects blood pH and the concentrations of bicarbonate and hydrogen ions.	CC.1.19	MS-3
I.8.7	Apply knowledge of the equation for the bicarbonate buffer system to predict how changing the bicarbonate concentration or blood pH affects the P _{CO2} of plasma.	CC.1.19	MS-3
I-9 Control of Pulmonary Ventilation			
I.9.1	Describe the locations and functions of the central nervous system centers involved in the generation and control of cyclic breathing.	CC.2.7	
I.9.2	Compare and contrast the locations and functions of the central and peripheral chemoreceptors associated with the control of ventilation.	CC.2.3	
I.9.3	Diagram or describe the reflex control of ventilation, including the major stimuli, sensors, neural control pathways, and targets.	CC.2.4, CC.2.5 CC.2.8	MS-4
I.9.4	Predict and explain how changes in the levels of CO ₂ , O ₂ , and/or pH in the plasma or cerebrospinal fluid will impact ventilation.	CC.2.3, CC.2.10 CC.5.1, CC.6.3	MS-3
I.9.5*	Explain why it is possible to hold one's breath longer after hyperventilating than after eupnea (normal breathing).	CC.2.11 CC.6.6	
I.9.6*	Describe the physiological basis of shallow water blackout during a breath-hold dive that follows intentional hyperventilation.	CC.6.6	
I.9.7*	Describe the pulmonary reflexes (e.g., in response to irritants, hyperinflation).	CC.2.8	
I-10 Application			
I.10.1	Describe the immediate changes that occur in P _{O2} (atmospheric and arterial), hemoglobin saturation, and ventilation when a person goes from sea level to high altitude (e.g., 8,000 ft above sea level).	CC.2.4	PS-1
I.10.2	Given a factor or situation (e.g., pulmonary fibrosis, pneumothorax), predict the changes that could occur in the respiratory system and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.2.10	PS-1
I.10.3*	Given a disruption in the structure or function of the respiratory system (e.g., atelectasis), predict the possible factors that might have created the disruption (i.e., given an effect, predict possible causes).	CC.2.11	PS-1

MODULE I Blood

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

- EC-1 Atoms and molecules (EC.1.1)
- EC-2 Biological energy (EC.2.3, EC.2.4, EC.2.5)
- EC-3 Chemical bonds and reactions (EC.3.5, EC.3.7, EC.3.9)
- EC-5 Biological reactions (EC.5.6, EC.5.7, EC.5.8, EC.5.9)
- EC-6 Solutions and solubility (EC.6.1, EC.6.3, EC.6.4, EC.6.6, EC.6.7, EC.6.8)
- EC-7 General organization of the cell (EC.7.1, EC.7.2)

Module A Cell Physiology & Membrane Processes

- A-1 Cell membrane structure & function (A.1.1)
- A-2 Movement of materials across cell membranes (A.2.1, A.2.3, A.2.10)
- A-3 Body fluid compartments (A.3.2, A.3.6)
- A-4 Epithelial transport (A.4.1, A.4.3, A.4.4)

Module B Cell-Cell Communication & Control Systems

- B-1 Cell-to-cell communication (B.1.1, B.1.2, B.1.5)
- B-2 Chemical signaling pathways (B.2.2, B.2.3, B.2.7)

Module D Cellular Neurophysiology

- D-1 Neurons, glial cells, and neurotransmitters (D.1.7, D.1.9, D.1.10*)

Module E Systems Neurophysiology

- E-1 Organization and general properties of the nervous system (E.1.2, E.1.5, E.1.8)
- E-4 Peripheral nervous system: efferent divisions (E.4.1, E.4.3, E.4.4)
- E-5 Reflexes and integrated control of movement (E.5.6*)
- E-6 Peripheral nervous system: sensory division (E.6.4, E.6.12*)

Module G Cardiovascular Physiology

- G-1 General structure and function of the cardiovascular system (G.1.1, G.1.3, G.1.4, G.1.6, G.1.8, G.1.9)
- G-2 Gross and microscopic anatomy of the heart (G.2.4)
- G-7 Blood flow and blood pressure (G.7.2, G.7.3, G.7.4, G.7.6, G.7.7, G.7.8, G.7.9, G.7.10, G.7.11, G.7.22, G.7.23, G.7.26*)
- G-9 Capillaries and lymph (G.9.4, G.9.5, G.9.8, G.9.9)

Module H Blood

H-1 Composition of blood (I.1.1, I.1.2, I.1.6)
H-2 Erythrocytes (1.2.2, I.2.3, 1.2.9*)

Related LOs covered in other modules

Module K Fluid-Electrolyte & Acid-Base Homeostasis

K-8 Acid-base homeostasis (K.8.4)

Module P Integrative Function

P-1 Thermoregulation (P.1.5*)

P-2 Exercise physiology (P.2.2, P.2.3, P.2.6*)

P-4 Physiology of extreme environments *

High altitude (P.4.1*, P.4.2*)

Diving (P.4.4*, P.4.5*)

Space (P.4.6*, P.4.7*)

P-5 Integrated response to COVID (P.5.1*, P.5.2*)

P-6 Integrated physiological functions (P.6.10)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in J.3.10*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO J Renal physiology

Module J Renal Physiology covers the function of the kidneys and urinary tract, including renal blood flow and micturition. The discussions of loop function, urine concentration/dilution, endocrine control of kidney functions, and the renal handling of hydrogen ions and bicarbonate ions are found in Module K *Fluid-Electrolyte and Acid-Base Homeostasis*.

This body system, like the respiratory system, has significantly overlap with the cardiovascular system and provides an opportunity to show students how functions are integrated.

Notes: Physiologists separate excretion (removal of urine from the body) from the functional processes of the nephron (filtration, reabsorption, and secretion).

Students frequently do not recognize that once a substance has moved from the blood into the lumen of the nephron, that substance is now in the external environment and will be excreted unless there is a mechanism by which it can be reabsorbed back into the ECF. The renal pelvis and lumens of the ureters, bladder, and urethra are all part of the external environment.

The collecting duct is distinct from the nephron as multiple nephrons empty into a single collecting duct. However, the collecting duct is commonly presented with the nephron to simplify integrated fluid handling mechanisms.

Terminology: Nephron loop is the preferred term for the loop of Henle.

Prior to beginning this module, students should have an understanding of:

- basics of epithelial transport in Module A *Cell Physiology & Membrane Processes*
- chemical signaling pathways in Module B *Cell-Cell Communication & Control Systems*
- control of peripheral resistance and capillary filtration in Module G *Cardiovascular Physiology*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.2, CC.1.4)

Compartmentation (CC.1.8, CC.1.11)

Mass and energy balance (CC.1.14)

Molecular structure and function (CC.1.18-CC.1.22)

Properties of physical systems (CC.1.27)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.4, CC.2.6)

Control pathways (CC.2.10-CC.2.12)

CC-3 Gradients and Flow (CC.3.1, CC.3.3-CC.3.5)

CC-4 Energy Types, Storage, Use and Conversion (CC.4.6, CC.4.7)

CC-6 Systems Integration (CC.6.3, CC.6.5, CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (J.3.10, J.4.24, J.4.25, J.6.1- J.6.4)

Quantitative Reasoning (QR)

QR-2 Select and use appropriate mathematical relationships to solve problems. (J.3.7, J.4.2, J.4.12, J.4.13, J.4.14, J.4.18)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (J.4.21, J.4.22, J.4.23)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (J.2.5, J.3.9, J.3.12, J.3.13, J.4.7, J.4.10, J.4.15)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (J.3.6, J.4.4, J.4.5)

PLO J Renal physiology			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
J-1 Anatomy of the Urinary System			
J.1.1	List the gross anatomical structures of the urinary system and describe their functions.	CC.1.2 CC.1.8	
J.1.2	Diagram or describe the structures in a cross-sectional diagram of a kidney (e.g., the renal cortex, renal medulla, renal pelvis, renal artery, renal vein, and ureter).		MS-4
J.1.3	Describe the structure and list the function of the renal corpuscle (e.g., glomerulus and glomerular capsule [Bowman's capsule]).	CC.1.8 CC.1.27	
J.1.4	Diagram or describe the segments of the nephron in the order in which a filtered solute encounters them (e.g., glomerular capsule [Bowman's capsule], proximal convoluted tubule, nephron loop [loop of Henle], distal convoluted tubule).	CC.1.8	MS-4
J.1.5	Explain the relationship between a nephron and its associated collecting duct.	CC.1.11	
J.1.6	Compare and contrast the anatomy and locations of cortical nephrons and juxtamedullary nephrons.		
J.1.7	List and describe the vascular elements associated with the nephron (e.g., afferent and efferent arterioles, glomerulus, peritubular capillaries, vasa recta).		
J.1.8	Describe the pathway taken by a water molecule from the time it enters the afferent arteriole until it leaves the body in urine.		
J.1.9	Describe the pathway taken by a water molecule to the renal vein, from the time it enters the afferent arteriole into the nephron, is reabsorbed into the blood from the proximal tubule, and leaves the kidney in the renal vein.		
J-2 Functions and Processes of the Urinary System			
J.2.1	Describe the major functions of the kidneys.	CC.1.2	

J.2.2	Describe the major functions of the urinary tract.	CC.1.2	
J.2.3	Define <i>renal filtration</i> , <i>reabsorption</i> , and <i>secretion</i> .	CC.1.11	
J.2.4	Compare and contrast reabsorption and secretion in the nephron describing the direction of solute and water movement and location where each process occurs (i.e., the renal tubule segments).	CC.1.11	
J.2.5	Explain how the integration of renal filtration, reabsorption, and secretion determines the volume and composition of the urine.	CC.1.14	MS-3
J.2.6	Compare the average daily volumes and osmolarities of glomerular filtrate entering the nephrons and urine leaving the collecting ducts.		
J.2.7	Compare and contrast the composition of blood plasma and glomerular filtrate.		
J.2.8	Compare and contrast renal secretion and renal excretion.	CC.1.11	
J-3 Glomerular Filtration			
J.3.1	Diagram or describe the following microscopic structures associated with the glomerular filtration barrier (e.g., afferent and efferent arterioles, glomerular capillaries, podocytes, mesangial cell, glomerular [Bowman's] capsule).	CC.1.4 CC.1.8	MS-4
J.3.2	List and describe the properties of the layers comprising the glomerular filtration barrier of the renal corpuscle (e.g., glomerular capillary endothelium, capillary basement membrane, podocytes).	CC.1.27	
J.3.3	Describe the properties of the glomerular filtration barrier that determine the composition of the filtrate that enters the glomerular (Bowman's) capsule.	CC.1.4 CC.1.11	
J.3.4	Explain how podocytes and mesangial cells function to change the available surface area for glomerular filtration.	CC.1.27	
J.3.5	Define <i>glomerular filtration rate</i> (GFR) and list typical values in volume per minute and volume per day.		
J.3.6	Diagram or describe the roles of blood pressure (hydrostatic pressure), capsule fluid pressure, and colloid osmotic (oncotic) pressure in determining net filtration pressure.	CC.3.1 CC.3.3	MS-4
J.3.7	Given the capillary hydrostatic and oncotic pressures and capsule fluid pressure, calculate the net filtration force at the glomerular capillaries.	CC.3.1 CC.3.5	QR-2
J.3.8	Compare and contrast the pressures responsible for glomerular filtration to the pressures that drive fluid reabsorption in the peritubular capillaries.	CC.3.1	

J.3.9	Predict the changes in net filtration pressure that occur when hydrostatic pressure decreases and colloid osmotic pressure increases as blood travels along the length of the glomerular capillary.	CC.3.1 CC.3.5	MS-3
J.3.10*	Describe factors that might change renal blood pressure, capsule fluid pressure, and colloid osmotic (oncotic) pressure (e.g., hypotension, protein malnutrition), and predict their effect on GFR.	CC.3.1 CC.3.5	PS-1
J.3.11	Compare and contrast renal blood flow and renal plasma flow [renal plasma volume/time = (renal blood volume minus hematocrit)/time].		
J.3.12	Explain the relationship between glomerular filtration rate (GFR) and filtration fraction (FF), and list typical values for GFR and FF.		MS-3
J.3.13	Predict the effect of changes in the resistance of the afferent or efferent arteriole on renal blood flow and glomerular filtration rate (GFR).	CC.3.3 CC.3.4	MS-3
J.3.14	Describe autoregulation of glomerular filtration rate (GFR) and list the range of mean blood pressures within which GFR is autoregulated.	CC.2.4	
J.3.15	Describe the structures, locations, and functions of the juxtaglomerular cells (JG or granular cells) and macula densa of the juxtaglomerular apparatus (JGA).	CC.1.27	
J.3.16	Define <i>tubuloglomerular feedback</i> and describe the mechanism of tubuloglomerular feedback that mediates autoregulation of glomerular filtration rate (GFR).	CC.2.4	
J.3.17	Describe the endocrine and neural control of renal arteriolar resistance, including neurotransmitters and their receptors.	CC.3.4	
J-4 Renal Handling of Solutes			
J.4.1	Describe the approximate percentage of filtrate that is reabsorbed in each segment of the nephron.		
J.4.2	For the important solutes of the body (e.g., Na ⁺ , K ⁺ , glucose, urea), compare the filtration rate of the solute to its excretion rate (i.e., the net handling of the solute by the nephron).		QR-2
J.4.3	For the important solutes of the body (e.g., Na ⁺ , K ⁺ , glucose, urea), describe how each segment of the nephron handles the solute (reabsorption, secretion, or both).	CC.1.11 CC.1.18 CC.1.19	
J.4.4	Diagram or describe the cellular mechanism for Na ⁺ reabsorption across the epithelium of the proximal tubule, naming apical and basolateral transporters and classifying the transporters as active or passive.	CC.1.4 CC.4.7	MS-4

J.4.5	Diagram or describe the cellular mechanism for Na ⁺ -dependent reabsorption of glucose across the epithelial cells of the proximal tubule, naming apical and basolateral transporters and classifying the transporters as active or passive.	CC.4.6 CC.4.7	MS-4
J.4.6	List examples of direct active transport, indirect (e.g., secondary) active, and passive transepithelial renal transport, including the substance being transported, any membrane proteins involved, and the direction of movement across the tubule wall (e.g., glucose is reabsorbed from the proximal tubule using apical Na ⁺ -glucose cotransport [secondary active transport] and basolateral GLUT facilitated diffusion transporters).	CC.4.6 CC.4.7	
J.4.7	Use reabsorption of Na ⁺ , water, and urea in the proximal tubule to compare and contrast active and passive mechanisms for transport across the epithelium.	CC.1.4 CC.4.7	MS-3
J.4.8	Describe how filtrate osmolarity changes as the filtrate passes through each segment of the nephron and describe the range of possible urine osmolarities leaving the collecting duct.		
J.4.9	Define <i>renal clearance</i> .		
J.4.10	Compare and contrast the concepts of renal clearance of a substance, renal handling of the substance, and renal excretion rate of a substance.	CC.1.14	MS-3
J.4.11	State the equation for clearance of a solute.	CC.1.14	
J.4.12	Explain how inulin clearance and creatinine clearance can be used to determine glomerular filtration rate (GFR).		QR-2
J.4.13*	Apply the clearance equation to estimate renal plasma flow and renal blood flow for an appropriate compound.		QR-2
J.4.14	Explain using mathematical reasoning how renal filtration, reabsorption, and secretion rates determine the excretion rate of a solute (i.e., excretion = filtration - reabsorption + secretion).		QR-2
J.4.15	Predict how renal clearance of a solute changes if filtration, reabsorption, or secretion of the solute are altered.		MS-3
J.4.16*	Describe the cellular transport processes involved in eliminating drugs (e.g., penicillin), wastes, and foreign substances in the proximal tubule.	CC.1.20 CC.1.22 CC.4.7	
J.4.17*	Explain the process by which filtered proteins are reabsorbed in the proximal tubule.	CC.1.11 CC.4.7	

J.4.18*	Given data such as plasma and urine concentrations of a solute, GFR, and urine flow rate, calculate the filtration rate, excretion rate, or clearance of a solute (e.g., inulin, creatinine, para-amino hippuric acid [PAH], glucose, and penicillin).		QR-2
J.4.19	Define <i>renal threshold</i> and <i>transport maximum</i> (T_m) for a filtered solute.	CC.1.20 CC.1.21	
J.4.20	Explain the concepts of saturation, renal threshold, and transport maximum (T_m) in the context of protein-mediated reabsorption of glucose in the proximal tubule.	CC.1.20 CC.1.21	
J.4.21	Graph or describe the effect of increasing plasma concentration of a compound on filtration rate, reabsorption rate, secretion rate, and urine excretion of the compound.	CC.1.20 CC.1.21 CC.2.6	QR-5
J.4.22	Use a graph demonstrating the effect of plasma concentration of a compound on filtration rate, reabsorption rate, secretion rate, and urine excretion of the compound to identify the transport maximum (T_m) and the renal threshold.	CC.1.20 CC.1.21	QR-5
J.4.23*	Interpret the net renal handling of a solute from a graph showing the effect of solute plasma concentration on the solute's filtration rate, reabsorption rate, secretion rate, and urinary excretion rate.	CC.1.20 CC.1.21 CC.2.6	QR-5
J.4.24	Explain how specificity and competition for a transporter can be used to enhance or inhibit excretion of a substance (e.g., concurrent administration of probenecid with penicillin to decrease penicillin secretion).	CC.1.18 CC.1.22	PS-1
J.4.25	Describe how drugs that act as transporter antagonists can be used to alter excretion of a substance (e.g., SGLT2 antagonists).	CC.1.18 CC.1.22	PS-1
J-5 Micturition			
J.5.1	Classify urinary tract structures as smooth or skeletal muscle (e.g., bladder, internal urethral sphincter, external urethral sphincter).		
J.5.2	Diagram or describe the micturition (urination) reflex, including the role of stretch receptors and somatic, sympathetic, and parasympathetic neurons.	CC.2.12	MS-4
J.5.3	Compare and contrast the locations, innervations, and functions of the internal urethral sphincter and external urethral sphincter.		
J.5.4	Describe voluntary control of micturition, including changes in the activity of specific neural pathways.		
J-6 Application			
J.6.1	Given a factor or situation (e.g., hyperglycemia), predict the changes that might occur in renal function and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.2.10 CC.6.6	PS-1

J.6.2	Given a disruption in renal or urinary tract structure or function (e.g., glucose in the urine), predict the possible factors or situations that might have caused that disruption (i.e., given an effect, predict possible causes).	CC.2.11 CC.6.6	PS-1
J.6.3	Predict the change in renal blood flow and glomerular filtration rate that would result from an increase in renal sympathetic nerve activity.	CC.2.4 CC.6.3 CC.6.5 CC.6.6	PS-1
J.6.4	Predict the effect on GFR if the urinary tract was obstructed at or distal to the renal pelvis.	CC.6.6	PS-1

MODULE J Renal Physiology

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

EC-1 Atoms and molecules (EC.1.4)
 EC-2 Biological energy (EC.2.1-EC.2.3, EC.2.5)
 EC-3 Chemical bonds and reactions (EC.3.5, EC.3.7)
 EC-4 Organic compounds (EC.4.2, E.4.5, EC.4.6)
 EC-5 Biological reactions (EC.5.2, EC.5.4, EC.5.6, EC.5.8, EC.5.9)
 EC-6 Solutions and solubility (EC.6.1-EC.6.5)
 EC-7 General organization of a cell (EC.7.1- EC.7.4)
 EC-8 Cellular membrane structure and function (EC.8.1-EC.8.3)

Module A Cell Physiology & Membrane Processes

A-1 Cell membrane structure and function (A.1.1)
 A-2 Movement of materials across cell membranes (A.2.4-A.2.11)
 A-3 Body Fluid Compartments (A.3.1, A.3.2, A.3.5)
 A-4 Epithelial transport (A.4.1, A.4.2, A.4.4, A.4.5, A.4.7)
 A-5 Water movement across membranes (A.5.1, A.5.3)
 A-6 Osmolarity and tonicity (A.6.1, A.6.2)

Module B Cell-Cell Communication & Control Systems

B-1 Cell-to-cell communication (B.1.1, B.1.2, B.1.3, B.1.6, B.1.7)
 B-2 Chemical signaling pathways (B.2.1-2.3, B.2.5-2.12, B.2.15, B.2.16)

Module G Cardiovascular Physiology

G-7 Blood flow and blood pressure (G.7.7, G.7.12, G.7.19, G.7.21, G.7.22, G.7.23, G.7.24)

G-8 Regulation of blood pressure (G.8.7)

G-9 Capillaries and lymph (G.9.4, G.9.5)

Module H Blood

H-1 Composition of blood (H.1.1, H.1.2, H.1.3)

Related LOs covered in other modules

Module C Endocrine Physiology

C.5.4* - renal reabsorption of calcium

Module K Fluid-Electrolyte & Acid-Base Homeostasis

This module has discussions of loop function, urine concentration/dilution, endocrine control of kidney functions, and the renal handling of hydrogen ions and bicarbonate ions.

Module P Integrated Function

P-4 Physiology of extreme environments: (P.4.1*, P.4.6*, P.4.7*)

P-5 Integrated physiological functions (P.6.8, P.6.9)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in K.2.6*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO K Fluid-Electrolyte & Acid-Base Homeostasis

PLO K Fluid-Electrolyte & Acid-Base Homeostasis focuses on the integration of body function and demonstrates how multiple organ systems communicate and work together to maintain homeostasis (core concept CC.6.3). In particular, Section K-7 *Integrated control of blood volume, blood pressure, and osmolarity* and Section K-8 *Acid-base homeostasis* address the coordinated responses of the cardiovascular, renal, respiratory, nervous, and endocrine systems to homeostatic challenges.

Prior to beginning this module, students should have an understanding of:

- movement of materials across membranes, body fluid compartments, epithelial transport, and osmolarity and tonicity in Module A *Cell Physiology & Membrane Processes*
- chemical signaling pathways in Module B *Cell-Cell Communication & Control Systems*
- endocrine control pathways in Module C *Endocrine Physiology*
- neural control pathways in Module E *Systems Neurophysiology*
- blood pressure and its control in Module G *Cardiovascular Physiology*
- the relationship between CO₂, H⁺, and pH in Module I *Respiratory Physiology*
- glomerular filtration and renal handling of solutes in Module J *Renal Physiology*
-

See Background Basics at the end of this document for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.6)

Compartmentation (CC.1.9, CC.1.11)

Mass and energy balance (CC.1.13, CC.1.14)

Molecular structure and function (CC.1.16-CC.1.18)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.1-CC.2.6)

Control pathways (CC.2.8, CC.2.10-CC.2.12)

CC-3 Gradients and Flow (CC.3.1, CC.3.3)

CC-4 Energy Types, Storage, Use and Conversion (CC.4.7)

CC-5 Communication (CC.5.1)

CC-6 Systems Integration (CC.6.1, CC.6.3, CC.6.5, CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (K.1.3, K.1.6, K.2.6, K.3.3, K.3.4, K.10.1, K.10.2, K.10.3, K.10.5)

PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (K.9.5)

Quantitative Reasoning (QR)

QR-2 Select and use appropriate mathematical relationships to solve problems. (K.3.5, K.4.3, K.8.10)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (K.1.2, K.2.5, K.4.2, K.5.4, K.7.1, K.8.6, K.8.8, K.9.3, K.9.4, K.10.4)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (K.2.2, K.2.4, K.5.1, K.6.1, K.7.4-K.7.10, K.8.7, K.8.9, K.8.12-K.8.15)

PLO K Fluid-Electrolyte & Acid-Base Homeostasis			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
K-1 Fluid and Electrolyte Homeostasis			
K.1.1	Describe the typical physiological routes of body water entry and loss.	CC.1.11 CC.1.13	
K.1.2	Predict how a net water loss or gain will change body fluid volume and osmolarity, and how these disturbances in turn alter the volume and osmolarity of the urine.	CC.2.1 CC.2.6	MS-3
K.1.3	Predict how a net NaCl loss or gain changes body fluid volume and osmolarity, and how these disturbances in turn alter the rate of urine production and the osmolarity of the urine.	CC.1.13, CC.2.6 CC.3.3	PS-1
K.1.4	Explain the contributions of the nephron loop [of Henle] to the formation of concentrated (hyperosmotic) urine.	CC.3.1 CC.3.3	
K.1.5	Explain the role of the ascending limb of the nephron loop [of Henle] in producing a high renal interstitial fluid osmolarity and a dilute urine.	CC.1.11 CC.3.1	
K.1.6	Apply the concept of mass balance to explain why the kidneys can compensate for excess fluid (water) intake but cannot correct a state of water deficiency.	CC.1.13 CC.1.14	PS-1
K-2 Water Balance and Vasopressin			
K.2.1	Describe behavioral mechanisms that help maintain body osmolarity (e.g., thirst, salt appetite).	CC.1.13, CC.2.1 CC.2.6, CC.6.3	
K.2.2	Using a negative feedback pathway, diagram or describe the reflex release of vasopressin (ADH, antidiuretic hormone), including stimuli, location and role of relevant sensors, locations of vasopressin synthesis and release, target tissue(s), and response(s).	CC.2.8, CC.2.12 CC.6.3	MS-4
K.2.3	Describe the action of vasopressin (ADH) on the distal nephron (distal tubule and collecting duct) and its effect on the final concentration of urine.	CC.1.11	
K.2.4	Diagram or describe the cellular mechanism by which vasopressin (ADH) increases tubule permeability to water, including the role of aquaporin channels and membrane recycling.	CC.1.11 CC.1.16	MS-4
K.2.5	Apply understanding of the action of vasopressin (ADH) on the kidney to predict the major consequences of vasopressin (ADH) deficiency or hypersecretion.	CC.2.5, CC.2.10 CC.6.5, CC.6.6	MS-3

K.2.6*	Compare and contrast central (CNS-based) and nephrogenic diabetes insipidus based on plasma vasopressin (ADH) levels and for each condition, predict the response to an injection of vasopressin (ADH).	CC.6.6	PS-1
K-3 Sodium Balance			
K.3.1	Identify the typical physiological routes of sodium (Na^+) loss from the body.	CC.1.11	
K.3.2	Describe sodium distribution in the body fluid compartments.	CC.1.11	
K.3.3	Explain the role of Na^+ in maintaining extracellular fluid volume.	CC.2.4, CC.2.5 CC.2.6, CC.6.3	PS-1
K.3.4	Describe the relationship between sodium balance, blood volume, and arterial blood pressure.	CC.2.6	PS-1
K.3.5*	Given plasma Na^+ concentration and glomerular filtration rate (GFR), calculate the filtered load of Na^+ .	CC.1.13	QR-2
K.3.6	Identify the renal tubule sites of Na^+ reabsorption and describe which locations are subject to endocrine or neural control.	CC.2.8, CC.4.7	
K-4 Potassium Balance			
K.4.1	Describe potassium (K^+) distribution in the body fluid compartments and the major routes of K^+ excretion.	CC.1.11	
K.4.2	Explain the importance of maintaining potassium homeostasis with regard to membrane potential and list examples of dysfunction that occur when plasma potassium levels are elevated (hyperkalemia) or too low (hypokalemia).	CC.2.1, CC.2.3 CC.2.6, CC.2.10	MS-3
K.4.3*	Given plasma K^+ concentration and glomerular filtration rate (GFR), calculate the filtered load of K^+ .	CC.1.13, CC.3.3	QR-2
K.4.4	Identify the renal tubule sites of K^+ reabsorption and secretion, and describe which locations are subject to endocrine or neural control.	CC.2.8, CC.4.7 CC.6.3	
K-5 Angiotensin and Aldosterone			
K.5.1	For the renin-angiotensin system (RAS), diagram or describe the factors that initiate renin release, the pathway from angiotensinogen to angiotensin II (ANGII), and the effects of ANGII on target tissues.	CC.2.8, CC.2.12 CC.6.3	MS-4
K.5.2	Describe the major physiological stimuli that cause release of aldosterone from the adrenal cortex (suprarenal gland cortex).	CC.2.8	

K.5.3	Diagram or describe the effect of aldosterone on the nephron, including the tubule segments involved and the transport mechanisms that are altered by aldosterone.	CC.1.11, CC.1.18 CC.4.7	MS-4
K.5.4	Apply knowledge of the typical action of aldosterone to predict the signs and symptoms of aldosterone deficiency or hypersecretion.	CC.6.5 CC.6.6	MS-3
K-6 Natriuretic Peptides			
K.6.1	Diagram or describe the stimuli that cause release of natriuretic peptide hormones (e.g., ANP, BNP), their sites of synthesis, and their effects on the nephron and other target tissues (e.g., adrenal cortex).	CC.2.8	MS-4
K.6.2	Describe the change in renal blood flow and glomerular filtration rate (GFR) caused by release of natriuretic peptides.	CC.2.12	
K-7 Integrated Control of Blood Volume, Blood Pressure, and Osmolarity			
<i>“Integrated control” means the coordinated responses of the cardiovascular, nervous, endocrine, and urinary systems.</i>			
K.7.1	Predict how blood pressure changes when blood volume decreases significantly due to dehydration or hemorrhage.	CC.5.1, CC.6.5 CC.6.6	MS-3
K.7.2	Compare changes in body osmolarity in response to dehydration versus hemorrhage.	CC.2.6, CC.2.10 CC.5.1, CC.6.6	
K.7.3	List the types and locations of sensors (receptors) in the cardiovascular, nervous, endocrine, and urinary systems that monitor blood volume, blood pressure, or osmolarity.	CC.2.8, CC.5.1 CC.6.1, CC.6.3	
K.7.4	Diagram or describe the integrated response to hemorrhage (blood volume decreases, osmolarity is unchanged).	CC.2.6, CC.5.1 CC.6.3, CC.6.6	MS-4
K.7.5	Diagram or describe the body’s integrated response to excessive salt ingestion (no change in body water volume, osmolarity increases).	CC.2.6, CC.5.1 CC.6.3, CC.6.6	MS-4
K.7.6*	Diagram or describe the body’s integrated response to ingestion of hypertonic saline (NaCl) (volume increases, osmolarity increases).	CC.2.6, CC.5.1 CC.6.3, CC.6.6	MS-4
K.7.7*	Diagram or describe the body’s integrated response to ingestion or infusion of isotonic saline (NaCl) (volume increases, osmolarity is unchanged).	CC.2.6, CC.5.1 CC.6.3, CC.6.6	MS-4
K.7.8	Diagram or describe the body’s integrated response to dehydration, such as due to sweat loss or diarrhea (volume decreases, osmolarity increases).	CC.2.6, CC.5.1 CC.6.3, CC.6.6	MS-4

K.7.9	Diagram or describe the body's integrated response to excessive water ingestion (volume increases, osmolarity decreases).	CC.2.6, CC.5.1 CC.6.3, CC.6.6	MS-4
K.7.10*	Diagram or describe the body's integrated response to sweat loss replaced by drinking water (volume is unchanged, osmolarity decreases).	CC.2.6, CC.5.1 CC.6.3, CC.6.6	MS-4
K-8 Acid-base Homeostasis			
K.8.1	Define the average and healthy pH range for arterial blood.	CC.2.1	
K.8.2	Explain the effect of pH changes outside the normal range on molecular and cellular mechanisms (e.g., enzyme activity, protein shape).	CC.1.17, CC.1.18 CC.2.1	
K.8.3	Describe the major buffer systems of the different body compartments.	CC.1.9	
K.8.4	Compare and contrast metabolic and respiratory sources of acid and explain the typical physiological routes of acid loss from the body.	CC.1.11 CC.6.3	
K.8.5	Define the normal ranges for arterial blood P_{CO_2} and HCO_3^- .		
K.8.6	Using the equation $CO_2 + H_2O \leftrightarrow H^+ + HCO_3^-$, predict how plasma pH changes when arterial blood P_{CO_2} and HCO_3^- concentrations change.	CC.2.2 CC.2.6	MS-3
K.8.7	Diagram or describe the relationship between transport of carbon dioxide in the blood and the bicarbonate buffer system of the plasma.	CC.2.2	MS-4
K.8.8	Explain how changes in alveolar ventilation (e.g., hypoventilation, hyperventilation) affect arterial blood P_{O_2} , arterial blood P_{CO_2} , arterial blood pH, and arterial blood HCO_3^- .	CC.2.10 CC.6.5	MS-3
K.8.9	Diagram or describe the reflex pathways that link changes in plasma P_{CO_2} or pH to changes in ventilation.	CC.2.5, CC.2.6 CC.2.8, CC.5.1	MS-4
K.8.10*	Given plasma concentration and glomerular filtration rate (GFR), calculate the filtered load of HCO_3^- .	CC.1.13	QR-2
K.8.11	List the major sites of bicarbonate reabsorption or secretion along the nephron.	CC.1.11	
K.8.12	Diagram or describe the proximal tubule mechanisms for reabsorbing filtered bicarbonate ions and explain the role of carbonic anhydrase in this process.	CC.1.11	MS-4
K.8.13*	Diagram or describe the mechanism by which type A intercalated cells in the collecting duct help maintain homeostasis during acidosis.	CC.1.11 CC.2.6	MS-4

K.8.14*	Diagram or describe the mechanism by which type B intercalated cells in the collecting duct help maintain homeostasis during alkalosis.	CC.1.11 CC.2.6	MS-4
K.8.15*	Diagram or describe the mechanisms by which the nephron secretes or reabsorbs hydrogen ions, including the role of urinary buffers.	CC.1.11 CC.2.6	MS-4
K-9 Disturbances of pH Homeostasis			
K.9.1	Define <i>acidosis</i> and <i>alkalosis</i> .		
K.9.2	Compare and contrast metabolic and respiratory causes of pH imbalances.	CC.6.5	
K.9.3	Describe the general mechanisms of respiratory and renal compensations for disruptions of pH homeostasis.	CC.1.11, CC.2.6 CC.5.1	MS-3
K.9.4	Given a sudden increase or decrease in the pH of extracellular fluid, predict how buffers, respiratory mechanisms, and renal mechanisms act to minimize the change.	CC.2.6, CC.6.1 CC.6.3, CC.6.5 CC.6.6	MS-3
K.9.5*	Given arterial blood values for P_{CO_2} , pH, and HCO_3^- , predict the changes to acid-base balance (e.g., acidosis or alkalosis), and if the cause of the pH disturbance is metabolic or respiratory.	CC.2.11 CC.6.6	PS-4
K.9.6*	Describe the K^+ shift between intracellular and extracellular compartments caused by acidosis.	CC.1.9, CC.1.11 CC.1.13	
K-10 Application			
K.10.1	Given a factor or situation (e.g., excessive ingestion of bicarbonate antacids, bulimia), predict the changes that might occur in function and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.2.10 CC.6.6	PS-1
K.10.2	Given a disruption in function (e.g., inability to create a concentrated urine), predict the possible factors or situations that might have caused that disruption (i.e., given an effect, predict possible causes).	CC.2.10 CC.6.6	PS-1
K.10.3	Given the mechanism of action of a specific diuretic, predict potential side effects of the drug on electrolyte homeostasis.	CC.2.10 CC.6.6	PS-1
K.10.4	Apply understanding of vasopressin action to explain the consequences of administering a drug that acts as an antagonist to the vasopressin receptor.	CC.1.6, CC.2.10 CC.6.6	MS-3
K.10.5	Predict the effects of prolonged vomiting or diarrhea on acid-base and fluid-electrolyte homeostasis.	CC.6.6	PS-1

MODULE K Fluid-Electrolyte & Acid-Base Homeostasis

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

- EC-1 Atoms and molecules (EC.1.4)
- EC-2 Biological energy (EC.2.3, EC.2.5)
- EC-3 Chemical bonds and reactions (EC.3.5, EC.3.7, EC.3.9)
- EC-4 Organic compounds (EC.4.2)
- EC-5 Biological reactions (EC.5.6-EC.5.9)
- EC-6 Solutions and solubility (EC.6.2, EC.6.4-EC.6.8)
- EC-7 General organization of a cell (EC.7.1, EC.7.2)
- EC-8 Cellular membrane structure and function (EC.8.1-EC.8.3)

Module A Cell Physiology & Membrane Processes

- A-1 Cell membrane structure and function (A.1.1)
- A-2 Movement of materials across cell membranes (A.2.1-A.2.8, A.2.10, A.2.11)
- A-3 Body fluid compartments (A.3.1-A.3.6)
- A-4 Epithelial transport (A.4.1, A.4.2, A.4.4, A.4.7)
- A-5 Water movement across membranes (A.5.1, A.5.3)
- A-6 Osmolarity and tonicity (A.6.1, A.6.2*, A.6.3, A.6.6, A.6.7, A.6.9, A.6.10*)

Module B Cell-Cell Communication & Control Systems

- B-1 Cell-to-cell communication (B.1.1-B.1.5, B.1.8*)
- B-2 Chemical signaling pathways (B.2.1-B.2.10)

Module C Endocrine System

- C-1 General principles of endocrinology (C.1.3, C.1.6, C.1.7, C.1.10, C.1.11*, C.1.12*)
- C-1 Chemical classification of hormones and mechanisms of hormone action at receptors (C.1.13, C.1.16)

Module E Systems Neurophysiology

- E-1 Divisions of the nervous system (E.1.2)
- E-1 Functional organization of the nervous system (E.1.5, E.1.8)
- E-4 Peripheral nervous system: efferent divisions (E.4.1, E.4.2, E.4.4, E.4.5, E.4.6)

Module G Cardiovascular Physiology

- G-1 General structure and functions of the cardiovascular system (G.1.2)
- G-6 Control of heart rate, stroke volume, and cardiac output (G.6.7, G.6.12)
- G-7 Blood flow and blood pressure (G.7.3, G.7.7, G.7.18, G.7.21, G.7.22, G.7.27)
- G-8 Regulation of blood pressure (G.8.2, G.8.3, G.8.5, G.8.8)

Module I Respiratory Physiology

I-2 Pulmonary ventilation (I.2.3, I.2.15)

I-5 Gas exchange in the lungs and tissues (I.5.5)

I-8 Carbon dioxide transport in blood (I.8.1, I.8.2, I.8.5*, I.8.6, I.8.7)

I-9 Control of pulmonary ventilation (I.9.1-I.9.4)

Module J Renal Physiology

J-2 Functions and processes of the urinary system (K.2.1, J.2.3-J.2.7)

J-3 Glomerular filtration (J.3.4-J.3.9, J.3.10*, J.3.13, J.3.14, J.3.16, J.3.17)

J-4 Renal handling of solutes (J.4.3, J.4.6, J.4.18*)

Related LOs covered in other modules**Module A Cell Physiology & Membrane Processes**

A-3 Body fluid compartments (A.3.7*, A.3.8*, A.3.9*)

A-6 Osmolarity and tonicity (A.6.4, A.6.5, A.6.8)

Module G Cardiovascular Physiology

G-9 Capillaries and lymph (G.9.5, G.9.10*)

Module J Renal Physiology

J-4 Renal handling of solutes (J.4.24, J.4.25)

Module P Integrated Function

P-4 Physiology of extreme environments*

High altitude (P.4.1*, P.4.2*)

Space (P.4.6*, P.4.9*)

P-5 Integrated response to COVID* (P.5.2*, P.5.3*)

P-6 Integrated physiological functions (P.6.8, P.6.9)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
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- Advanced learning outcomes are indicated with an asterisk, as in L.1.7*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO L Digestive physiology

PLO L Digestive Physiology discusses digestion and absorption of nutrients by the digestive system. Concepts related to nutrient metabolism, metabolic pathways, and energy balance are covered in Module M *Metabolism and Metabolic Control*. The organization of topics and content for the digestive system in a traditional physiology course differs significantly from that of a combined anatomy & physiology course.

Using the physiologist's process-centered approach to the digestive system, this module is organized by the three digestive phases: cephalic phase, gastric phase, and intestinal phase, which includes both the small and large intestines. Physiologists consider the four digestive processes to be digestion, secretion, motility, and absorption. Excretion (defecation) is discussed but not considered a digestive process. Ingestion (moving material from the environment into the mouth) is behavioral and is discussed with hunger, appetite, and satiety (Module M *Metabolism and Metabolic Control*).

Immune functions of the digestive system are addressed here rather than in Module O *Immune System*.

Terminology:

- The terms “gut” and “gastrointestinal (GI) tract” in this document refer to the stomach and intestines. The term is sometimes applied more broadly to the entire digestive system from mouth to anus, and sometimes more narrowly to mean only the intestines.
- We have retained the eponym for interstitial cells of Cajal (ICC) because of the widespread, continued use of the term in physiology, pathophysiology, and medicine, and also because there are unrelated interstitial cells in other organs (e.g., the testes).

Prior to beginning this module, students should have an understanding of:

- basics of epithelial transport in Module A *Cell Physiology & Membrane Processes*
- chemical signaling pathways in Module B *Cell-Cell Communication & Control Systems*
- autonomic and enteric divisions in Module E *Systems Neurophysiology*
- organization of the circulatory system in Module G *Cardiovascular Physiology*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure - Function Relationships

Anatomy and levels of organization (CC.1.2-CC.1.5)

Compartmentation (CC.1.8-CC.1.12)

Mass balance and energy balance (CC.1.13, CC.1.14)

Molecular structure and function (CC.1.15-CC.1.17)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.4, CC.2.6, CC.2.7)

Control pathways (CC.2.8-CC.2.12)

CC-5 Communication (CC.5.1)**CC-6 Systems Integration** (CC.6.1-CC.6.4, CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (L.6.34, L.9.6, L.9.7)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions and refine hypotheses about a physiological process, system or disease. (L.5.9, L.6.16, L.9.5, L.9.9, L.9.10)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (L.1.3, L.1.5, L.2.3, L.3.1, L.3.2, L.4.7, L.5.7, L.5.8, L.6.6, L.6.10, L.6.11, L.6.15, L.6.18, L.6.20, L.6.25, L.6.27, L.6.28, L.6.30, L.6.35, L.6.39, L.6.43, L.6.45, L.7.1, L.7.8, L.9.2, L.9.3)

PLO L Digestive physiology

At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
L-1 Anatomy Overview of the Digestive System			
L.1.1	List and classify the organs of the gastrointestinal tract (GI tract, digestive tract, alimentary canal, gut) versus the accessory organs of the GI tract.		
L.1.2	Define <i>sphincter</i> and explain the function of sphincters relevant to the GI tract and accessory organs.	CC.1.10	
L.1.3	Diagram or describe the pathway taken by an ingested substance through the GI tract, identifying each organ and sphincter the substance passes through.	CC.1.8 CC.1.9	MS-4
L.1.4	List and describe the macroscopic (e.g., rugae, circular folds [plicae circulares]) and microscopic (e.g., villi, microvilli) structures of the gut that increase surface area.	CC.1.12	
L.1.5	Diagram or describe the layers of the stomach wall from mucosa to serosa, then compare and contrast the layers of the stomach to the layers of the intestinal wall.	CC.1.3 CC.1.4	MS-4
L.1.6	Compare and contrast the arrangement of the muscle layer (muscularis externa) of GI tract in the stomach versus a section of the small intestine.		
L.1.7*	Compare and contrast the muscular composition (i.e., skeletal versus smooth) of the upper and lower esophagus, and upper and lower esophageal sphincters.		
L.1.8	Briefly describe the components and organization of the enteric nervous system (ENS) and its relationship to the autonomic nervous system and explain why the ENS is sometimes called “the little brain” or “the brain in the gut.”		
L.1.9*	Compare and contrast intrinsic and extrinsic neurons of the enteric nervous system (ENS).		
L-2 Functions of the Digestive System			
L.2.1	Describe the primary functions of the digestive system (i.e., digestion, absorption, secretion, and motility) and identify the locations where each process occurs.	CC.1.2	

L.2.2	Explain the process of excretion in the gastrointestinal (GI) tract (defecation), and identify the location where excretion occurs.	CC.1.11	
L.2.3	Diagram or describe fluid balance in the digestive system, identifying the sources and relative volumes of fluid entering and exiting the gastrointestinal tract daily (e.g., fluid ingestion, digestive secretions, fluid absorption, excretion).	CC.1.13 CC.1.14	MS-4
L.2.4	Compare the average volume of fluid ingested in a day to the volume secreted by the digestive tract and its accessory organs in a day.	CC.1.13	
Motility			
L.2.5	Compare and contrast tonic contraction of gastrointestinal smooth muscle with phasic contractions and identify locations where each occurs.		
L.2.6*	Describe slow wave potentials and the role of the interstitial cells of Cajal (ICC) in gastrointestinal (GI) tract smooth muscle.	CC.2.7	
L.2.7	Define, compare and contrast <i>segmental contractions</i> and <i>peristaltic contractions</i> , and identify the locations where each occurs in the gastrointestinal (GI) tract.	CC.1.11	
L.2.8*	Define the <i>migrating motor complex</i> (MMC) of the digestive tract and describe its function.	CC.2.7	
L.2.9*	Apply knowledge of smooth muscle function to classify a region of gastrointestinal (GI) tract smooth muscle as single-unit or multi-unit.		
L.2.10	Describe, compare and contrast the motility patterns that occur in the small intestine during eating or fasting.		
L-3 Control of Digestive Function			
L.3.1*	Diagram or describe the neural reflex pathway (short-loop pathway) within the enteric nervous system (ENS) including the location of sensory receptors, integration center, role of enteric neurons, targets, and target responses.	CC.2.8	MS-4
L.3.2	Diagram or describe the integration of information between the enteric nervous system (ENS) and the central nervous system (CNS) in the regulation of digestive function.	CC.2.4 CC.5.1 CC.6.1	MS-4
L.3.3	Compare and contrast the general effects of sympathetic and parasympathetic innervation on digestive function.	CC.5.1	
L.3.4	Describe the source, stimuli for release, targets, and target responses of the major gastrointestinal (GI) tract hormones (e.g., gastrin, cholecystokinin [CCK], secretin).	CC.2.12 CC.6.1	

L-4 Cephalic Phase of Digestion			
L.4.1	Define the <i>cephalic phase</i> of digestion.		
L.4.2	Explain how external stimuli (e.g., the smell or thought of food) can initiate the feedforward cephalic phase of digestion.	CC.2.9 CC.6.1	
L.4.3	Define <i>bolus</i> and describe how structures of the oral cavity contribute to mechanical digestion (e.g., mastication) of food, and bolus formation.	CC.1.12	
L.4.4	Describe the salivary glands, their function, and secretions that contribute to the chemical digestion of food.	CC.1.5	
L.4.5*	Describe the composition of saliva and the functions of each chemical component (e.g., mucus, water, salivary amylase).		
L.4.6*	Describe the cellular processes involved in secretion of saliva by salivary gland epithelium.		
L.4.7	Diagram or describe the steps of the deglutition (swallowing) reflex, including the actions of the tongue, soft palate, pharynx, epiglottis, esophagus, and esophageal sphincters.	CC.1.11	MS-4
L-5 Gastric Phase of Digestion			
L.5.1	Define <i>gastric phase of digestion</i> .		
L.5.2	List and identify the regions of the stomach (e.g., fundus, body, antrum, pylorus).	CC.1.8	
L.5.3	Describe the general functions of the stomach (e.g., digestion, storage, defense).	CC.1.10	
L.5.4	Define <i>chyme</i> and list the secretions of the gastric mucosa (e.g., gastric acid [HCl], mucus, pepsin), their stimuli for release, associated cell types, and describe the function of each.	CC.1.5	
L.5.5*	Describe how gastric motility in each region of the stomach contributes to physiological functions (e.g., storage, receptive relaxation).	CC.1.11	
L.5.6*	Describe the source of gastrin-releasing peptide (GRP) and its role in digestion.		
L.5.7	Diagram or describe the integrated functions of gastric acid (HCl), gastric lipase, and pepsin in chemical digestion in the stomach.	CC.6.1	MS-4
L.5.8	Diagram or describe the cellular mechanism for the production and secretion of HCl by parietal cells, including the role of carbonic anhydrase.		MS-4
L.5.9*	Apply understanding of parietal HCl secretion to explain why eating a meal is accompanied by alkalization of blood leaving the stomach (alkaline tide).	CC.2.6	MS-3

L.5.10	Explain the importance of the acidic environment of the stomach for the initiation of enzymatic protein digestion.	CC.1.16	
L.5.11*	Explain the functions of gastric paracrine secretions (e.g., histamine, intrinsic factor, and somatostatin [SS]).	CC.5.1	
L-6 Intestinal Phase of Digestion			
L.6.1	Define <i>intestinal phase of digestion</i> .		
L.6.2	Describe the divisions of the small intestine (duodenum, jejunum, ileum), and structures linking the accessory organs: liver, pancreas, and gallbladder.	CC.1.8	
L.6.3	Describe the general functions of the small intestine (e.g., absorption, peristalsis).	CC.1.2 CC.1.4	
L.6.4	Compare and contrast the volume and composition of chyme entering and exiting the small intestine.	CC.1.13	
L.6.5	Explain how the rate of gastric emptying, enzyme secretion, and acid (HCl) secretion is matched to the rate of intestinal digestion based on feedback loops between the stomach and duodenum.	CC.1.13 CC.2.9	
L.6.6	Diagram or describe the structural and functional relationships among structures of the intestine and vessels (i.e., villi, microvilli, brush border, crypts, lacteals, and blood vessels).	CC.1.12	MS-4
L.6.7*	Describe the location and function of intestinal stem cells and explain their significance.		
Intestinal phase: accessory organs			
L.6.8	Describe the secretions of the liver, pancreas, and gallbladder related to gastrointestinal (GI) function (i.e., endocrine and exocrine pancreatic secretions, bile).	CC.1.2 CC.1.5	
L.6.9	Compare and contrast the microscopic structure and functions of the endocrine and exocrine pancreas.	CC.1.5	
L.6.10	Diagram or describe the structure and functional significance of the hepatic portal system.	CC.6.2	MS-4
L.6.11	Diagram or describe the microscopic organization of a liver lobule including hepatocytes, associated blood vessels, and bile ducts.		MS-4
L.6.12*	Compare and contrast bile salts and bile acids.		
Intestinal phase secretion			
L.6.13	Identify the sources and describe the functions of the secretions released into the intestinal lumen (e.g., digestive enzymes, bile, bicarbonate, mucus, and isotonic NaCl solution).	CC.6.3	

L.6.14	Explain the mechanism by which acidic chyme from the stomach is neutralized in the duodenum (i.e., by pancreatic secretions).		
L.6.15	Diagram or describe the mechanism by which epithelial cells of the small intestine and exocrine pancreas produce and secrete a sodium bicarbonate solution into the lumen, including the role of carbonic anhydrase.	CC.1.4	MS-4
L.6.16*	Apply knowledge of secretion of isotonic NaCl and bicarbonate solutions in the digestive system to predict the physiological consequences of defective CFTR channels (cystic fibrosis transmembrane regulator channels).	CC.2.10 CC.6.6	MS-3
L.6.17	Explain the importance of inactive enzymes (zymogens, proenzymes) in the digestive system (e.g., pepsinogen, trypsinogen) and identify locations where they are found.	CC.1.17	
L.6.18	Diagram or describe the mechanism by which inactive pancreatic enzymes are activated in the small intestine, including the relationships among enteropeptidase (enterokinase), trypsinogen, and trypsin.	CC.1.17 C.1.19	MS-4
L.6.19	Define <i>brush border</i> and explain the adaptive significance of brush border enzymes anchored to the apical membrane of the enterocyte.	CC.1.12	
L.6.20	Diagram or describe the anatomic pathway for bile secretion, the role of the gallbladder, and the hormone that promotes this secretion (i.e., CCK).	CC.1.11	MS-4
	Digestion and absorption of fats		
L.6.21	List and describe the common lipids and lipid-related molecules in the diet (e.g., cholesterol, long-chain fatty acids, triglycerides).	CC.1.15	
L.6.22*	Compare and contrast fats (triglycerides, also called triacylglycerols) lipids.		
L.6.23	Define <i>emulsification</i> and explain how the amphipathic structure of bile salts assists in emulsification of fats.	CC.1.17	
L.6.24	Describe the size, shape, and molecular composition of micelles.	CC.1.17	
L.6.25	Diagram or describe the roles and sources of lipase, phospholipase, and colipase in fat digestion.	CC.1.17 C.1.19	MS-4
L.6.26	Compare and contrast the mechanisms that transport cholesterol, triglycerides, and fatty acids from the intestinal lumen across the apical membrane of the enterocytes.	CC.1.11	
L.6.27	Diagram or describe the formation and composition of chylomicrons and explain how they exit the enterocyte.	CC.1.11	MS-4

L.6.28	Diagram or describe the anatomical pathway by which chylomicrons enter the venous blood.	CC.1.11	MS-4
L.6.29	Explain why the recycling of bile salts is essential for adequate fat digestion.	CC.1.13	
L.6.30*	Diagram or describe the role of the ileum in recycling of bile salts.		MS-4
	Carbohydrate digestion and absorption		
L.6.31	List common carbohydrates in the diet, describe their structures, and explain why some cannot be digested by humans.	CC.1.15	
L.6.32	Identify the enzyme responsible for glucose polymer breakdown, its source/location(s) in the GI tract, and the products that result from this breakdown.		
L.6.33	List the enzymes responsible for digestion of common disaccharides in the diet (i.e., sucrose, maltose, and lactose), and identify sources in the GI tract.		
L.6.34*	Explain why functional loss of a disaccharidase (i.e., sucrase, maltase, lactase) results in diarrhea.	CC.2.10	PS-1
L.6.35	Diagram or describe the cellular mechanisms by which enterocytes absorb monosaccharides.	CC.1.11	MS-4
L.6.36	Describe the pathway by which absorbed monosaccharides enter the blood.	CC.1.11	
	Protein digestion and absorption		
L.6.37	List the common enzymes involved in protein digestion, sources of these enzymes, and identify where they are found in the GI tract.	CC.1.9	
L.6.38*	Compare and contrast the actions of endopeptidases (proteases) and exopeptidases in the breakdown of polypeptides and proteins.		
L.6.39	Diagram or describe the mechanism by which enterocytes move amino acids from the lumen into the extracellular fluid.	CC.1.11	MS-4
L.6.40*	Compare and contrast the absorption of di- and tripeptides by an enterocyte to the absorption of other small peptides.	CC.1.11	
L.6.41	Describe the anatomic pathway by which digested peptides and amino acids enter the blood.		
	Nucleic acid, vitamin, and mineral digestion and absorption		
L.6.42	List the breakdown products of nucleic acid polymers (e.g., DNA, RNA) that are absorbed by the intestine.		
L.6.43	Diagram or describe the mechanisms for intestinal absorption of Na ⁺ , K ⁺ , Cl ⁻ ions and water.	CC.1.11	MS-4

L.6.44	Compare and contrast the mechanisms for absorption of fat-soluble vitamins (e.g., vitamins A, D, E, K) and water-soluble vitamins (e.g., vitamin C and most B vitamins) by the intestine.	CC.1.11	
L.6.45*	Explain the role of intrinsic factor in the absorption of vitamin B12.	CC.1.11	
L.6.46*	Diagram or describe the cellular mechanism for intestinal iron absorption.	CC.1.11	MS-4
L-7 Excretion and the Large Intestine			
L.7.1	Diagram or describe the gross anatomy of the large intestine: cecum, appendix, colon, rectum, and anal canal.	CC.1.2 CC.1.8	MS-4
L.7.2	Describe the organization of smooth muscle in the wall of the colon and compare it to the organization of the small intestine.		
L.7.3	Describe the general functions of the large intestine.	CC.1.2	
L.7.4	Compare the volume and composition of chyme entering the large intestine with the usual volume and composition of feces.	CC.1.14	
L.7.5	Explain the role of the ileocecal valve in the gastroileal reflex.	CC.1.11	
L.7.6	Describe mass movement in the colon and explain its role in the gastrocolic reflex and defecation.	CC.1.11	
L.7.7	Compare and contrast the location, composition, and innervation (i.e., somatic motor versus autonomic) of the internal and external anal sphincters.	CC.6.4	
L.7.8	Diagram or describe the steps of the defecation reflex.	CC.2.8	MS-4
L-8 Immune Function of the GI Tract & the Gut Microbiome			
L.8.1	Describe the immune functions of the GI tract, including the roles of gut-associated lymphoid tissue (GALT), Peyer patches (lymphoid nodules), and microfold (M) cells.	CC.1.2	
L.8.2*	Describe the functional relationship between the enteric nervous system and immune system.	CC.6.1	
L.8.3	Explain the role of vomiting and diarrhea in digestive system immune function.	CC.1.13	
L.8.4	Explain how pathogenic bacteria such as <i>E. coli</i> can live in the large intestine without causing illness.	CC.1.8	
L.8.5	Define <i>gut microbiome</i> and describe its significance in human health and disease (e.g., digestion of complex carbohydrates, vitamin K production).		
L.8.6*	Describe the role of the gut microbiome and colonocytes in bile acid recycling.		

L-9 Integration and Application			
L.9.1	Explain the role of the digestive system in fluid and osmotic balance.	CC.1.2 CC.1.13	
L.9.2*	Diagram or describe the integration of cephalic and gastric phases of digestion through neural reflex pathways (i.e., long-loop [vagal] and short-loop [local] reflexes).	CC.5.1 CC.6.1	MS-4
L.9.3	Diagram or describe the key processes and control pathways associated with the cephalic, gastric, and intestinal phase of digestion, including key secretions.	CC.2.12	MS-4
L.9.4*	Compare and contrast the slow wave potentials of GI smooth muscle to the action potentials of skeletal muscle and the pacemaker potentials of cardiac muscle.	CC.2.7	
L.9.5	Apply understanding of gastric function to predict effects of exogenous drugs on digestion in the stomach, i.e., H ₂ receptor antagonists (e.g., ranitidine), proton pump inhibitors (e.g., omeprazole), antacids (e.g., calcium carbonate).	CC.2.10	MS-3
L.9.6*	Describe the mechanism that explains why stopping the use of proton pump inhibitors (PPIs) may cause a sudden increase in acid secretion (i.e., a rebound effect).	CC.2.11	PS-1
L.9.7 *	Compare and contrast the integrated feedback between the small intestine and stomach in regulation of gastric enzyme and acid secretion for a protein meal versus a carbohydrate meal.	CC.6.1	PS-1
L.9.8	Explain the mechanisms protecting the stomach from autodigestion.		
L.9.9	Given a factor or situation (e.g., absence of lactase in the small intestine), predict the changes that might occur in the digestive system and the consequences of those changes (i.e., given a cause, state possible effects).	CC.2.10 CC.6.6	MS-3
L.9.10	Given a disruption in the structure or function of the digestive system (e.g., diarrhea), predict the possible factors or situations that might have created that disruption (i.e., given an effect, predict possible causes).	CC.2.11 CC.6.6	MS-3

MODULE L Digestive physiology

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

- EC-1 Atoms and molecules (EC.1.2)
- EC-2 Biological energy (EC.2.3, EC.2.5, EC.2.6)
- EC-3 Chemical bonds and reactions (EC.3.4, EC.3.5, EC.3.9)
- EC-4 Organic compounds (EC.4.2-EC.4.6)
- EC-5 Biological reactions (EC.5.5-EC.5.9)
- EC-6 Solutions and solubility (EC.6.1, EC.6.3, EC.6.4, EC.6.6-EC.6.8)
- EC-7 General organization of a cell (EC.7.1, EC.7.2, EC.7.4)
- EC-8 Cell membrane structure and function (EC.8.1-E.C.8.3)

Module A Cell Physiology & Membrane Processes

- A-1 Cell membrane structure function (A.1.1)
- A-2 Movement of materials across cell membranes (A.2.1-A.2.11)
- A-3 Body fluid compartments (A.3.1, A.3.2, A.3.5)
- A-4 Epithelial transport (A.4.1-A.4.8)
- A-5 Water movement across membranes (A.5.1-A.5.3)
- A-6 Osmolarity and tonicity (A.6.1, A.6.7)

Module B Cell-Cell Communication & Control Systems

- B-1 Cell-to-cell communication (B.1.1-B.1.7)
- B-2 Chemical signaling pathways (B.2.2, B.2.5, B.2.6)

Module E Systems Neurophysiology

- E-1 Organization and general properties of the nervous system (E.1.1, E.1.2, E.1.5, E.1.8)
- E-4 Peripheral nervous system: efferent divisions (all)
- E-6 Peripheral nervous system: sensory division (E.6.2, E.6.3, E.6.4, E.6.12*)

Related LOs covered in other modules. *These are LOs that instructors might expect to see in this module but that we chose to include elsewhere.*

Module E Systems Neurophysiology

- E-8 Olfaction and gustation (smell and taste) (E.8.2*, E.8.3, E.8.4)

Module K Fluid-Electrolyte & Acid-Base Homeostasis

K-10 Application (K.10.1, K.10.5)

Module M Metabolism & Metabolic Control discusses the fate of nutrients absorbed by the digestive system.

Module P Integrative Physiology

P-6 Integrated physiological functions (P.6.1, P.6.3, P.6.6-P.6.10)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in M.3.5*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO M Metabolism & Metabolic Control

Module M Metabolism & Metabolic Control introduces nutrients, metabolism, metabolic pathways, and energy balance relevant in a physiological context. Learning outcomes related to the hormones insulin and glucagon are presented in detail here rather than in Module C *Endocrine Physiology*. All metabolism discussed here refers to healthy individuals unless otherwise specified.

Prior to beginning this module, students should have an understanding of:

- biological energy, chemical bonds, and reactions from EC *Entering Competencies*
- chemical signaling pathways in Module B *Cell-Cell Communication & Control Systems*
- endocrine pathways from Module C *Endocrine Physiology*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure - Function Relationships

Anatomy and levels of organization (CC.1.5, CC.1.6)

Compartmentation (CC.1.10)

Mass balance and energy balance (CC.1.13, CC.1.14)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.6)

Control pathways (CC.2.8-CC.2.12)

CC-3 Gradients and Flow (CC.3.1, CC.3.3)**CC-4 Energy Types, Storage, Use and Conversion** (CC.4.1, CC.4.2, CC.4.4, CC.4.5, CC.4.7, CC.4.8)**CC-5 Communication** (CC.5.1)**CC-6 Systems Integration** (CC.6.1-CC.6.3, CC.6.6)**SKILLS** addressed in this module:**Process of Science (PS)****PS-1** Draw conclusions based on inference and evidence-based reasoning. (M.4.8, M.4.12)**Quantitative Reasoning (QR)****QR-2** Select and use appropriate mathematical relationships to solve problems. (M.1.7)**QR-5** Create and/or interpret graphs and other quantitative representations of physiological processes. (M.4.10, M.5.2)**Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)****MS-3** Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (M.4.3, M.5.3, M.5.4)**MS-4** Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (M.3.1, M.4.5, M.4.7, M.4.9, M.4.11)**PLO M - Metabolism & Metabolic Control**

At the end of an introductory one-semester physiology course, a student should be able to do the following		Core Concepts	Skills
M-1 Nutrients			
M.1.1	Define <i>nutrient</i> , <i>essential nutrient</i> , and <i>non-essential nutrient</i> .		
M.1.2	List the major (e.g., carbon, calcium, potassium, sodium) and minor (e.g., iron, copper, zinc) essential elements and list examples of physiological processes utilizing each.		
M.1.3	Relate nitrogen balance to protein intake and excretion.	CC.1.13 CC.1.14	
M.1.4	Identify the major storage sites (nutrient pools) in the body for carbohydrates, lipids, and proteins, and describe the composition of carbohydrates, lipids, and proteins in each site.	CC.1.10 CC.4.4	

M.1.5	Define <i>calorie</i> and <i>kilocalorie</i> (cal, kcal).	CC.4.5	
M.1.6	Compare the relative energy yields (kcal/gram) of carbohydrates, lipids, and proteins.	CC.4.5	
M.1.7	Use the relative energy yields (kcal/gram) of nutrients to calculate the energy content of a given food.	CC.4.5	QR-2
M-2 Metabolism and Metabolic Pathways			
M.2.1	Define <i>metabolism</i> , <i>anabolism</i> , and <i>catabolism</i> .		
M.2.2	Compare and contrast the fed (absorptive, postprandial) and fasted (post-absorptive, preprandial) states.		
M.2.3	Compare and contrast anabolism and catabolism, then list examples of common anabolic and catabolic reactions used for synthesis or degradation of biomolecules.	CC.4.7	
M.2.4	Compare and contrast carbohydrate, lipid, and protein metabolism in the fed (absorptive) and fasted (post-absorptive) states.		
M.2.5	Describe the roles of the liver, adipose tissue, and skeletal muscle in carbohydrate, lipid, and protein metabolism.	CC.4.4, CC.6.1 CC.6.3	
M.2.6	Compare and contrast the energy yield (i.e., ATP, NADH and FADH ₂) and products (e.g., CO ₂ , water, lactate) produced from catabolism of one glucose molecule under anaerobic conditions versus during aerobic respiration.	CC.4.1, CC.4.2 CC.4.5, CC.4.8	
M.2.7	Describe the anabolic and catabolic processes of carbohydrate metabolism (e.g., glycolysis, glycogenesis, glycogenolysis, gluconeogenesis).	CC.4.2 CC.4.4	
M.2.8	Describe the anabolic and catabolic processes of lipid metabolism (e.g., lipolysis, lipogenesis) and explain how products of these processes interact with the aerobic and anaerobic pathways for glucose metabolism.	CC.4.2 CC.4.4	
M.2.9	Describe the anabolic and catabolic processes of protein metabolism (e.g., deamination, transamination) and explain how products of these processes interact with the aerobic and anaerobic pathways for glucose metabolism.	CC.4.2 CC.4.4	
M.2.10	Explain the three primary fates of ingested biomolecules (i.e., energy, synthesis, and storage).	CC.4.2, CC.4.4 CC.4.7	
M-3 Energy Balance			
M.3.1	Diagram or describe the inputs and outputs that determine energy balance in the body (e.g., diet, heat, work) and the factors that influence them (e.g., hunger, exercise).	CC.1.13 CC.1.14 CC.4.2, CC.4.8	MS-4
M.3.2	Explain the relationship between oxygen consumption and metabolic rate.		

M.3.3	Describe a method that can be used to estimate a person's metabolic rate (e.g., indirect calorimetry).	CC.4.8	
M.3.4	Describe factors that affect metabolic rate (e.g., age, lean muscle mass, activity, diet, pathology).		
M.3.5*	Describe a current model of factors that influence appetite, food intake, and satiety (e.g., leptin and ghrelin).	CC.5.1 CC.6.2	
M-4 Endocrine Control of Metabolism			
M.4.1	Describe the effects of the following hormones on metabolism: insulin, glucagon, cortisol, growth hormone, and thyroid hormone.	CC.5.1 CC.6.1	
M.4.2	List the major hormones secreted from the endocrine pancreas (e.g., insulin, glucagon, somatostatin), list their cells of origin, and describe their chemical classification (e.g., peptide, protein).	CC.1.5	
M.4.3	Describe the integrated control of blood glucose homeostasis by insulin and glucagon.	CC.1.6 CC.2.12 CC.5.1, CC.6.1	MS-3
M.4.4	List the major targets for insulin (e.g., liver, muscle, adipose tissue), and describe the responses for each target.	CC.6.2	
M.4.5	Diagram or describe the reflex pathways for insulin secretion, including the role of neural input, gastrointestinal (GI) hormones, and feedforward control.	CC.2.8 CC.2.9	MS-4
M.4.6	Identify the primary target of glucagon and describe the target response.	CC.2.8 CC.6.2	
M.4.7	Diagram or describe the reflex pathway for glucagon secretion.	CC.2.8	MS-4
M.4.8*	Apply knowledge of the metabolic effects of insulin and glucagon to explain why ingestion of a pure protein meal (no carbohydrates) will trigger the release of both insulin and glucagon.	CC.6.1	PS-1
M.4.9*	Diagram or describe the interactions between metabolic pathways for carbohydrates, lipids, and proteins contributing to the maintenance of blood glucose homeostasis.	CC.2.6 CC.6.1	MS-4
M.4.10	Graph or describe the time course for the onset and duration of the biological actions of insulin following ingestion of a meal.	CC.6.3	QR-5
M.4.11	Diagram or describe the effects of a change in blood glucose concentration on insulin and glucagon secretion.	CC.2.10	MS-4
M.4.12	Predict the metabolic and physiological effects of insulin deficiency (type 1 diabetes mellitus), insulin excess, or decreased tissue responsiveness to insulin (insulin resistance, type 2 diabetes mellitus).	CC.2.10 CC.6.6	PS-1

M-5 Application

M.5.1*	Given the half-lives of insulin and glucagon, explain why continuous secretion is necessary for sustained responses.	CC.1.13 CC.5.1	
M.5.2*	Interpret graphs of glucose tolerance tests (GTT) from a sample of individuals (e.g., healthy, insulin-deficient/resistant) and explain the mechanisms responsible for differences in responses.		QR-5
M.5.3	Given a factor or situation (e.g., cirrhosis of the liver), predict the changes that might occur in metabolism and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.2.10 CC.6.6	MS-3
M.5.4	Given a disruption in metabolic function (e.g., high urine concentration of ketones), predict the possible factors or situations that might have created that disruption (i.e., given an effect, predict possible causes).	CC.2.11 CC.6.6	MS-3

MODULE M Metabolism & Metabolic Control

BACKGROUND BASICS from other modules. Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

EC-2 Biological energy (EC.2.1-EC.2.6)
 EC-3 Chemical bonds and reactions (EC.3.3, EC.3.5, EC.3.6, EC.3.7, EC.3.9)
 EC-4 Organic compounds (EC.4.1-EC.4.6)
 EC-5 Biological reactions (EC.5.1-EC.5.9)
 EC-7 General organization of a cell (EC.7.1, EC.7.2)
 EC-8 Cellular membrane structure and function (EC.8.1)
 EC-10 Cellular respiration (EC.10.1-EC.10.3)

Module A Cell Physiology & Membrane Processes

A-1 Cell membrane structure function (A.1.1)
 A-2 Movement of materials across cell membranes (A.2.1, A.2.4, A.2.8)
 A-3 Body fluid compartments (A.3.3)
 A-7 Membrane potential differences (A.7.7)

Module B Cell-Cell Communication & Control Systems

B-1 Cell-to-cell communication (B.1.3, B.1.4, B.1.5, B.1.8)
 B-2 Cell signaling pathways (B.2.2, B.2.4-B.2.6, B.2.9, B.2.15, B.2.16)

Module C Endocrine Physiology

C-1 General principles of endocrinology (C.1.4-C.1.10, C.1.13, C.1.17-C.1.19)

C-3 Thyroid hormones (C.3.9)

C-4 Growth and growth hormones (C.4.4)

Module E Systems Neurophysiology

E-1 Divisions of the nervous system (E.1.4, E.1.5)

E-4 Peripheral nervous system efferent divisions (E.4.1)

Related LOs covered in other modules**Module E Systems neurophysiology**

E-2 Meninges, cerebrospinal fluid, and blood-brain barrier (E.2.6*)

Module F Muscle Physiology

F-5 Muscle metabolism (F.5.1, F.5.3, F.5.4)

Module L Digestive Physiology

L-3 Control of digestive function (L.3.3)

L-6 Intestinal phases of digestion (L.6.26, L.6.27, L.6.36, L.6.39, L.6.40*, L.6.42)

Module P Integrative Function

P-2 Exercise (P.2.7*, P.2.8*, P.2.9*, P.2.10*)

P-6 Integrated physiological functions (P.6.1, P.6.4, P.6.13*)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in N.1.3*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO N Reproductive Physiology

The learning outcomes in **Module N Reproductive Physiology** are intended to introduce reproductive physiology as often taught in a limited-time introductory physiology survey course. We acknowledge that the content regarding “reproduction” in human physiology classes usually simplifies the reproductive systems to the binary sexes assigned at birth and reflects the approach that exists in most textbooks.

We have chosen to describe the typical binary assignment of sex at birth (*male or female*) with the term *prototypical* (the model on which something is based) when referring to structures and processes traditionally associated with the binary terms. The prototypical models provide a basis for students to understand the biological variability that can occur during development and the subsequent diversity of human reproductive physiology and anatomy.

Because of time constraints in a typical one-semester physiology course, we chose not to go into detail on the complex biopsychosocial topic of gender and to focus our learning outcomes on the biological aspects of sex. However, students should be able to distinguish between biological sex and gender (LO N.1.1). If an instructor is not limited by time, we recommend a broader, more accurate, and inclusive approach to teaching the topics of sex and gender.

Terminology

Based on a recent consensus statement (Cools et al. 2018) we will refer to congenital conditions that arise from atypical development at the genetic or anatomical level as “differences of sex development.”

Cools, M., Nordenström, CC., Robeva, R. *et al.* Caring for individuals with a difference of sex development (DSD): a Consensus Statement. *Nat Rev Endocrinol* **14**, 415–429 (2018).

<https://doi.org/10.1038/s41574-018-0010-8>

Prior to beginning this module, students should have an understanding of:

- genes and gene expression from EC *Entering Competencies*
- basics of epithelial transport and body compartments in Module A *Cell Physiology & Membrane Processes*
- chemical signaling pathways in Module B *Cell-Cell Communication & Control Systems*
- basics of hormone synthesis, transport, signaling, and control pathways in Module C *Endocrine Physiology*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Anatomy and levels of organization (CC.1.2, CC.1.8)

Compartmentation (CC.1.10, CC.1.11)

CC-2 Homeostasis and Control Pathways

Control pathways (CC.2.7-CC.2.12)

CC-5 Communication (CC.5.1)

CC-6 Systems Integration (CC.6.1, CC.6.4, CC.6.2, CC.6.6)

SKILLS associated with this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (N.2.10, N.7.2, N.9.3)

Quantitative Reasoning (QR)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (N.3.10, N.3.12, N.3.20)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (N.1.4, N.1.6, N.1.7, N.3.23, N.5.7, N.9.1, N.9.2, N.9.6-N.9.11)

MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (N.2.7, N.2.12, N.2.13, N.3.5, N.3.6, N.3.9, N.3.15, N.3.18, N.3.24, N.8.4, N.8.6)

PLO N Reproductive Physiology			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
N-1 Overview of Reproductive Systems			
N.1.1	Define, compare and contrast the following terms: <i>sex</i> , <i>gender</i> , <i>gender identity</i> , and <i>sexual orientation</i> .		
N.1.2	Describe, compare and contrast the anatomical structures and organs of the adult human reproductive systems.	CC.1.2	
N.1.3*	Describe the role of chromosomes (X & Y), genes and alleles (e.g., Rspo1, SRY), and gene expression in sex determination.		
N.1.4*	Compare and contrast the actions of androgens, estrogens, and anti-Mullerian hormone (AMH, previously Mullerian inhibiting substance) on the development of the gonad, paramesonephric/Mullerian duct, mesonephric/Wolffian duct, and external genitalia during fetal development.	CC.5.1	MS-3
N.1.5	Identify homologues of reproductive structures in adult humans (e.g., ovary is homologous to the testis).		
N.1.6	Compare and contrast the roles of hormones (e.g., gonadotropin releasing hormone [GnRH], follicle stimulating hormone [FSH], luteinizing hormone [LH], androgens, inhibin, estrogens, progesterone) involved in reproductive processes (e.g., gamete production, sex drive).		MS-3

N.1.7	Compare and contrast the processes of oocyte and sperm production with regard to the timing of meiotic divisions and the number of gametes produced from a single germ cell.		MS-3
N-2 Prototypical Male Reproduction			
	Anatomical structures		
N.2.1	Identify and describe the gross and microscopic structures of the male gonad.		
N.2.2	Identify and describe the structure and function of the spermatic cord and the transporting ducts (e.g., ductus [vas] deferens, ejaculatory duct, urethra).		
N.2.3	Identify and describe the structure and function of accessory glands (i.e., seminal glands [seminal vesicles], prostate gland, bulbourethral [Cowper] glands).		
N.2.4	Identify and describe the structure and functions of prototypical male external genitalia (e.g., scrotum, penis).		
N.2.5	Describe the pathway of sperm from the seminiferous tubules to the external urethral orifice of the penis.	CC.1.2	
N.2.6	Describe the composition and functions of semen.		
	Prototypical male endocrine physiology		
N.2.7	Diagram or describe the hypothalamic-pituitary-gonad axis and the feedback loops that control the production and regulation of androgens, inhibin, and androgen-binding protein in the testis.	CC.2.8 CC.2.9	MS-4
N.2.8*	Describe the biosynthesis and blood transport of testosterone and related androgens.		
N.2.9	List the major target organs and tissues of testosterone and related androgens and explain the hormonal mechanisms of action and the target responses (e.g., sperm production, fat deposition, muscle development).	CC.2.12 CC.6.1 CC.6.4	
N.2.10*	Predict the consequences of hypersecretion and hyposecretion of testosterone and related androgens in childhood, at puberty, and in reproductive life stages.	CC.2.10 CC.6.6	PS-1
	Spermatogenesis & spermiogenesis		
N.2.11	Define, compare and contrast the processes of <i>spermatogenesis</i> and <i>spermiogenesis</i> .		
N.2.12	Diagram or describe the steps of spermatogenesis in the seminiferous tubule, including the roles of nurse (sustentacular, [Sertoli]) and interstitial [Leydig] cells.	CC.1.8 CC.1.10	MS-4
N.2.13	Diagram or describe the endocrine control of spermatogenesis.	CC.2.12	MS-4
N.2.14	Describe the time course for production of a mature spermatozoa.		

N.2.15	Describe the process of spermiogenesis and compare the structural changes occurring in the immature spermatid to the structure and function of a mature spermatozoa.		
N-3 Prototypical Female Reproduction			
	Anatomical structures		
N.3.1	Identify and describe the gross and microscopic structures of the ovary.		
N.3.2	Identify and describe the structure and functions of the uterus and the transporting ducts (e.g., uterine [Fallopian] tubes/oviducts and vagina).	CC.1.11	
N.3.3	Identify and describe the structure and functions of the prototypical female external genitalia (e.g., mons pubis, labia majora, labia minora, clitoris, greater vestibular glands).		
N.3.4	Diagram or describe the pathway taken by an oocyte from the ovary to the uterus.	CC.1.2	MS-4
	Prototypical female endocrine physiology		
N.3.5	Diagram or describe the hypothalamic-pituitary-gonad axis and the feedback loops that control production and regulation of estrogens, progesterone, and inhibin in the ovary.	CC.2.8 CC.2.9	MS-4
N.3.6	Describe the biosynthesis and mechanism of transport in the blood for estrogens and progesterone.		
N.3.7	List the major targets of estrogens and progesterone, then explain the hormonal mechanism of action and the target responses (e.g., oogenesis, breast development, fat deposition).	CC.2.12	
N.3.8	Diagram or describe the phases of the ovarian cycle.	CC.2.7 CC.5.1	MS-4
N.3.9	Graph or describe the cyclic patterns of blood concentrations of GnRH, FSH, LH, estrogen, progesterone, and inhibin through the ovarian cycle.	CC.2.7	QR-5
N.3.10	Describe the phases of the uterine cycle and the structural changes in the uterine lining associated with each phase.	CC.2.7	
N.3.11	Graph or describe how estrogens and progesterone function to coordinate the timing of ovarian and uterine cycles into a menstrual cycle.	CC.2.7 CC.2.12	QR-5
N.3.12*	Relate hormonal control of the ovarian cycle to changes in basal body temperature through the cycle.	CC.2.7 CC.5.1	
	Oogenesis & folliculogenesis		
N.3.13	Define, compare and contrast the processes of <i>oogenesis</i> and <i>folliculogenesis</i> .		
N.3.14	Diagram or describe the stages of oogenesis in the ovary, including the roles of granulosa and theca cells.		MS-4

N.3.15	Describe the stages of folliculogenesis, including the roles of granulosa and theca cells.		
N.3.16	Identify the key events in oogenesis corresponding to each stage of follicular development.	CC.1.10	
N.3.17	Diagram or describe endocrine control of oogenesis and folliculogenesis by FSH, LH, estradiol, and inhibin, including the feedback loops.	CC.2.9 CC.2.12	MS-4
N.3.18	Explain how the processes of oogenesis and folliculogenesis span multiple ovarian cycles.	CC.2.7	
N.3.19	Define <i>ovulation</i> and relate the process to a graph showing patterns of estrogen, GnRH, and LH secretion through an ovarian cycle.	CC.2.7	QR-5
N.3.20	Describe the process of corpus luteum formation, including changes in granulosa and theca cells and their capacity to produce and secrete estrogens and progesterone.		
N.3.21	Describe the process of corpus luteum degradation into the corpus albicans, with associated changes in the production and secretion of estrogens and progesterone.		
N.3.22	Compare and contrast patterns of hormone secretion and corpus luteum lifespan in cycles when fertilization does or does not occur.	CC.2.11 CC.6.6	MS-3
N.3.23*	Relate gonadotropins, ovarian hormones, structural changes in the endometrium, and ovarian follicle development during a menstrual cycle.	CC.2.7 CC.2.12 CC.5.1	MS-3
N-4 Reproductive Function across Life Stages			
N.4.1	Define <i>puberty</i> .		
N.4.2	Compare and contrast development of secondary sex characteristics in prototypical males and females, including the average age of onset and completion at maturity.	CC.6.4	
N.4.3	Describe changes in the hypothalamic-pituitary-gonad axis that occur at the onset of puberty.		
N.4.4*	Define <i>menopause</i> and describe physiological changes in the female reproductive system with the onset of menopause.	CC.6.4	
N.4.5	Describe changes in the hormones of the hypothalamic-pituitary-gonad axis that occur at menopause.		
N.4.6	Describe age-associated physiological changes in the male reproductive system.	CC.6.4	
N-5 Sexual Response Cycle, Procreation, and Contraception			
N.5.1	Describe the four phases of the human sexual response cycle.	CC.2.12	
N.5.2	Describe the neural and vascular components of the erection reflex.	CC.2.12	
N.5.3	Define <i>emission</i> and <i>ejaculation</i> in the context of a sexual response cycle.	CC.1.11	

N.5.4	Describe the physiological responses of cardiovascular and respiratory systems during a sexual response cycle.	CC.6.2	
N.5.5	Compare and contrast the physiological mechanisms of common methods of birth control (e.g., rhythm, barrier, hormonal, chemical, surgical).		MS-3
N-6 Fertilization and Early Development			
N.6.1	Define <i>fertilization</i> , <i>zygote</i> , <i>cleavage</i> , <i>morula</i> , <i>blastocyst</i> , <i>embryo</i> , and <i>fetus</i> .		
N.6.2	Describe the process and specific events occurring before and at fertilization (e.g., sperm capacitation, acrosomal reaction, corona radiata penetration, zona pellucida penetration, fusion of the oocyte and sperm plasma membranes).		
N.6.3	Describe the role of the cortical reaction in preventing polyspermy.		
N.6.4*	Describe the timing and pattern of cell division occurring during transport of the dividing zygote to the uterus up until implantation.		
N-7 Pregnancy and Parturition			
N.7.1	Define <i>implantation</i> and describe the role of the trophoblast in the process of implantation.		
N.7.2*	Predict the consequences if a blastocyst implants outside the uterus (e.g., ectopic pregnancy).		PS-1
N.7.3	Describe the functions of the placenta.	CC.5.1	
N.7.4	Identify the source of human chorionic gonadotropin (hCG) and describe the role of hCG in the maintenance of the corpus luteum.	CC.5.1	
N.7.5*	Describe the dominant hormone(s) in each trimester of pregnancy and their source(s).	CC.5.1	
N.7.6	Define <i>parturition</i> and describe the three phases of labor.		
N.7.7*	Describe the roles of oxytocin, estrogen, relaxin, and prostaglandins during late pregnancy in preparation for parturition.		
N-8 Lactation			
N.8.1	Describe the structure and functions of the mammary glands.		
N.8.2	Define <i>lactation</i> .		
N.8.3*	Describe mammary gland development during pregnancy and the role of prolactin.		
N.8.4	Diagram or describe the endocrine regulation of lactation.	CC.2.12	MS-4
N.8.5	Describe the composition of milk.		
N.8.6	Diagram or describe the neuroendocrine reflex (the let-down reflex) responsible for milk ejection.	CC.2.12	MS-4
N-9 Application			
N.9.1	Compare methods used to predict the timing of fertility (e.g., rhythm method, basal body temperature).	CC.2.8	MS-3

N.9.2	Predict the physiological effects of exogenous compounds and drugs (e.g., estrogen replacement therapy, anabolic steroids, progesterone receptor antagonists).	CC.2.10	MS-3
N.9.3*	Describe the effects of hormone therapy in transgender medical care and explain why this is referred to as a second puberty.	CC.2.10 CC.6.6	PS-1
N.9.4	Define, compare and contrast terms <i>cisgender</i> and <i>transgender</i> and the implications of the sex assigned to an individual at birth.		
N.9.5	Define <i>differences of sex development</i> and describe some common examples (e.g., congenital adrenal hyperplasia, androgen insensitivity).		
N.9.6	Describe possible causes of amenorrhea or anovulatory cycles.	CC.2.11	MS-3
N.9.7	Identify the hormones detected by home pregnancy tests and home ovulation detection kits and relate the accuracy of the tests to the timing of hormone levels relative to conception or ovulation.		MS-3
N.9.8	Explain the hormonal basis of breast development in obese adult males.	CC.2.10	MS-3
N.9.9	Explain the process required to allow prototypical males to lactate.		
N.9.10	Given a factor or situation (e.g., removal of the gonads), predict the changes that might occur in the reproductive system and the consequences of those changes (i.e., given a cause, state possible effects).	CC.2.10 CC.6.6	MS-3
N.9.11	Given a disruption in the structure or function of the reproductive system (e.g., missing reproductive duct system), predict the possible factors or situations that might have created that disruption (i.e., given an effect, predict possible causes).	CC.2.11 CC.6.6	MS-3

MODULE N Reproductive Physiology

BACKGROUND BASICS from other modules. Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies

EC-6 Solutions and solubility (EC.6.3)

EC-7 General organization of a cell (EC.7.1-EC.7.4)

EC-8 Cellular membrane structure and function (EC.8.1)

EC-9 Genes, genomes, and gene expression (EC.9.1, EC.9.2, EC.9.4)

Module B Cell-Cell Communication & Control Systems

B-1 Cell-to-cell communication (B.1.1-B.1.8)

B-2 Chemical signaling pathways B.2.1-B.2.11, B.2.15, B.2.16)

B-3 Local chemical signal molecules (B.3.2*)

Module C Endocrine Physiology

C-1 General principles of endocrinology (C.1.1-C.1.3, C.1.5-C.1.8, C.1.9, C.1.12*)

C-1 Chemical classification of hormones and mechanisms of hormone action at receptors (C.1.13-C.1.15)

C-1 Control of hormone secretion (C.1.17, C.1.18)

C-2 Hypothalamus and pituitary gland (C.2.1, C.2.3-C.2.8)

Module E Systems Neurophysiology

E-4 Peripheral nervous system: efferent divisions (E.4.4)

Related LOs covered in other modules

Module C Endocrine Physiology

C-5 Calcium/phosphate homeostasis and bone (C.5.27)

Module I Respiratory Physiology

I-7 Oxygen transport in blood (I.7.14*)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in O.2.4*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO O Immune system

Module O Immune System describes a physiological system that includes all the defense mechanisms of the body. Anatomists usually refer to the lymphatic system, but to physiologists, the anatomic lymphatic system has functions that overlap three physiological systems. The lymphatics return fluid that escapes from capillaries to the venous circulation, they transport fats absorbed as chylomicrons at the intestine to the venous circulation, and they play a role in immune surveillance, as discussed in this module.

Lymph vessels are introduced in Module G *Cardiovascular Physiology* with capillary exchange, and they also appear in Module L *Digestive Physiology* related to chylomicron transport. Lymphoid tissues are discussed in this module. Blood typing can be found in Module H *Blood*. The immune function of the digestive tract and the microbiome are discussed in Module L *Digestive Physiology* because of the growing interest in the gut microbiome.

We recognize that many introductory physiology courses do not cover any of the immune system learning outcomes.

Prior to beginning this module, students should have an understanding of:

- membrane transport in Module A *Cell Physiology & Membrane Processes*

- chemical signaling pathways in Module B *Cell-Cell Communication & Control Systems*

See Background Basics at the end of this module for details.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure - Function Relationships

Anatomy and levels of organization (CC.1.2)

Compartmentation (CC.1.10, CC.1.11)

Molecular structure and function (CC.1.19)

CC-2 Homeostasis and Control Pathways

Control pathways (CC.2.10)

CC-5 Communication (CC.5.1)

CC-6 Systems Integration (CC.6.1, CC.6.6)

SKILLS addressed in this module:

Process of Science (PS)

PS-1 Draw conclusions based on inference and evidence-based reasoning. (O.5.3, O.8.5)

Quantitative Reasoning (QR)

QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes. (O.4.4, O.8.3)

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)

MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (O.8.1, O.8.2, O.8.4)

PLO O - Immune system			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
O-1 General Structure and Function			
O.1.1	Define <i>immunity</i> and describe the primary function of the immune system.		
O.1.2	Describe the structure, function, and major locations of primary and secondary lymphoid structures (e.g., organ-associated lymphoid tissues such as GALT and MALT, tonsils).	CC.1.2	
O.1.3	Compare and contrast the functions of lymphatic organs (e.g., lymph nodes, thymus, spleen).		
O.1.4	List and describe the functions of the six major types of leukocytes (i.e., eosinophils, neutrophils, basophils, monocytes/macrophages, dendritic cells, lymphocytes).		
O.1.5	Compare and contrast how chemical, physical, and mechanical barriers act as defense mechanisms in the body.	CC.1.10	
O.1.6	Define and explain the relationship between <i>pathogen</i> and <i>antigen</i> .		
O.1.7	Compare and contrast the basic types of pathogens (e.g., bacteria, viruses, fungi, parasites).		
O-2 Innate Immunity and Adaptive Immunity			
O.2.1	Define <i>innate (nonspecific) immunity</i> and <i>adaptive (specific) immunity</i> .		
O.2.2	Compare and contrast innate (nonspecific) with adaptive (specific) defenses in terms of the timing of response, specificity of response, and defenses utilized.		
O.2.3	List and describe the typical molecules involved in an innate immune response (e.g., opsonins, complement, histamine, chemotaxins) and their functions.	CC.1.19	
O.2.4*	Describe <i>extravasation</i> (diapedesis), <i>chemotaxis</i> , <i>opsonization</i> , and <i>membrane attack complex</i> formation, and explain their importance for innate (nonspecific) defenses.	CC.1.19	
O.2.5	Explain how the innate (nonspecific) and adaptive (specific) immune responses coordinate and cooperate in resistance to disease.	CC.5.1 CC.6.1	
O.2.6	List, compare and contrast the leukocytes involved in innate (nonspecific) and adaptive (specific) immune responses and their functions.		
O.2.7	Compare and contrast antibody-mediated (humoral) and cell-mediated (cellular) immunity in terms of mechanisms of action, time course, and response.	CC.1.19	

O-3 Phagocytosis and Antigen Presentation			
O.3.1	List the major phagocytic immune cells (e.g., neutrophils, macrophages) and explain the role of phagocytosis in the body's response to infection and injury.		
O.3.2	Describe the mechanism of phagocytosis and destruction of pathogens.	CC.1.19	
O.3.3	List the major cells that function as antigen-presenting cells (APCs) (e.g., dendritic cells, macrophages, and B-lymphocytes) and explain the role of APCs in adaptive (specific) immunity.		
O.3.4	Describe the mechanism of antigen presentation by antigen-presenting cells (APCs).	CC.1.11	
O-4 Antibody Function			
O.4.1	Define <i>antibody</i> , and diagram or describe the structure of an antibody protein.		
O.4.2	Explain the functions of antibodies (e.g., opsonization, agglutination, neutralization, activation of adaptive [specific] defenses) in an antibody-mediated (humoral) response.	CC.1.19	
O.4.3*	Compare and contrast the structure and functions of the five classes of antibodies.		
O.4.4	Graph or describe, then compare and contrast the time course of antibody production and the relative concentrations of antibodies in a primary and a secondary immune response.		QR-5
O.4.5	Describe and explain the physiological importance of <i>immunological memory</i> .		
O.4.6	Compare and contrast active and passive immunity with regard to the mode of acquisition of immunity and the presence/absence of immunological memory.	CC.6.1	
O-5 Inflammation			
O.5.1	List and explain the causes of the classic signs of inflammation (e.g., heat, swelling, and pain).		
O.5.2	Explain the benefits of local inflammation.		
O.5.3*	Predict the physiological consequences of systemic inflammation.		PS-1
O.5.4*	Describe the mechanism of fever, including the role of pyrogens.		
O.5.5	Explain the physiological benefits and risks of fever.		

O-6 Major Histocompatibility Complexes (MHC)			
O.6.1	Describe the function and locations of major histocompatibility complex proteins (MHC; also called human leukocyte antigens or HLA).	CC.1.19	
O.6.2*	Compare and contrast class I and class II major histocompatibility complex proteins (MHC I and MHC II) in terms of the type of antigens they display (endogenous/self vs. exogenous/nonself) and the type of cells that contain them (all nucleated cells vs. APCs).		
O.6.3*	Compare and contrast the functions of class I and class II major histocompatibility complex (MHC) proteins in adaptive (specific) immunity.		
O-7 Immune Tolerance			
O.7.1	Describe how the body differentiates between self and non-self, then predict the consequences of failure to recognize self (e.g., autoimmune disorders, blood transfusion reactions, organ donation rejection).	CC.5.1	
O.7.2	Describe how the body develops immune responses and lack of tolerance to non-harmful exogenous substances (e.g., gluten, latex).		
O-8 Application			
O.8.1	Given a factor or situation (e.g., widespread histamine release in an anaphylactic reaction), predict the changes that could occur in the body and the consequences of those changes (i.e., given a cause, state a possible effect).	CC.2.10 CC.6.6	MS-3
O.8.2	Given a disruption in the structure or function of the immune system (e.g., destruction of helper T-cells), predict the possible factors or situations that might have caused that disruption (i.e., given an effect, predict possible causes).	CC.2.10 CC.6.6	MS-3
O.8.3	Using a graph of primary and secondary immune responses, explain how vaccines work and the benefits of vaccine boosters.		QR-5
O.8.4*	Compare and contrast the body's responses to a bacterial infection versus a viral infection.		MS-3
O.8.5	Describe mechanical, physical, chemical, and behavioral mechanisms used to protect the body from infection (e.g., handwashing, face masks, condoms, water treatment, sanitation).		PS-1

MODULE O Immune System

BACKGROUND BASICS from other modules: Students need to understand and be able to apply these concepts in order to be successful in this module.

Entering Competencies:

EC-5 Biological reactions (EC.5.8, EC.5.9)

EC-7 General organization of a cell (EC.7.1, EC.7.2, EC.7.4)

Module A Cell Physiology & Membrane Processes

A-1 Cell membrane structure and function (A.1.1)

A-2 Movement of materials across cell membranes (A.2.9)

A-3 Body fluid compartments (A.3.1, A.3.2, A.3.6)

A-4 Epithelial transport (A.4.3, A.4.4)

Module B Cell-Cell Communication & Control Systems

B-1 Cell-to-cell communication (B.1.1, B.1.2)

B-2 Chemical signaling pathways (B.2.2-B.2.10, B.2.15)

B-3 Local chemical signal molecules (B.3.1*, B.3.2*)

Module G Cardiovascular Physiology

G-9 Capillaries and lymph (G.9.6, G.9.7, G.9.8)

Module H Blood

H-1 Composition of blood (H.1.1-H.1.5*, H.1.7, H.1.8*)

H-3 Leukocytes (H.3.1-H.3.3*)

Module I Respiratory Physiology

I-1 Structure and functions of the respiratory system (I.1.3, I.1.7*)

Related LOs covered in other modules. *These are LOs that instructors might expect to see in this module but that we chose to include elsewhere.*

Module N Digestive Physiology

N-8 Immune function of the GI tract & the gut microbiome

Module H Blood

H-6 ABO and Rh blood groups

Module P Integrative Function

P-1 Thermoregulation (P.1.4*)

P-2 Exercise (P.2.11*)

P-3 Integrated control of stress (P.3.2, P.3.4*)

P-5 Integrated response to COVID-19*

P-6 Integrated physiological functions (P.6.2, P.6.3, P.6.12)

How to use these learning outcomes:

- Select the LOs you wish to cover in your course, knowing that not all the LOs in this module may be suitable for your curriculum or students.
- The LOs are broad to allow for variability in the level of detail taught to different student populations. You must decide the appropriate details for your course.
 - (e.g., ...) in an LO means *For example, ...*. The examples listed after e.g., ... are not all-inclusive, and it is up to individual instructors to modify the terminology to fit their student populations.
 - (i.e., ...) means *in other words, ...* and is a way to restate the LO.
- Advanced learning outcomes are indicated with an asterisk, as in P.1.4*.
 - Advanced LOs address higher level skills or additional detail that may appear in some physiology texts but may not be appropriate for all introductory physiology classes.

PLO P Integrated Functions and Special Environments

Module P Integrated Function covers concepts related to two or more body systems working together to achieve homeostasis as well as the body's regulatory responses to special environmental challenges (e.g., stressors like exercise, climate, and altitude). The study of the interrelations between systems helps students recognize integrated body function.

While Module CC provides core concepts necessary for beginning study of physiology, this module ties concepts together to promote deeper understanding. Depending on the needs of the student population, instructors may teach selected topics throughout the semester where appropriate, utilize integrative learning outcomes for a capstone experience, or omit topics in this module entirely.

CORE CONCEPTS from Module CC. Students need to understand and be able to apply these core concepts in order to be successful in this module.

CC-1 Structure-Function Relationships

Compartmentation (CC.1.9, CC.1.11)

Mass balance and energy balance (CC.1.13)

Molecular structure and function (CC.1.16, CC.1.18)

CC-2 Homeostasis and Control Pathways

Homeostasis (CC.2.3-CC.2.5, CC.2.7)

Control Pathways (CC.2.9, CC.2.10, CC.2.12)

CC-3 Gradients and Flow (CC.3.3, CC.3.4)**CC-4 Energy Types, Storage, Use and Conversion** (CC.4.2-CC.4.5, CC.4.7, CC.4.8)**CC-5 Communication** (CC.5.1-CC.5.4)**CC-6 Systems Integration** (CC.6.1-CC.6.6)**SKILLS** addressed in this module:**Process of Science (PS)****PS-1** Draw conclusions based on inference and evidence-based reasoning. (P.1.4, P.2.11, P.4.3, P.4.8, P.4.9, P.6.11)**PS-4** Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions. (P.2.2, P.2.3)**Quantitative Reasoning (QR)****QR-5** Create and/or interpret graphs and other quantitative representations of physiological processes. (P.4.5)**Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)****MS-3** Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions, and refine hypotheses about a physiological process, system, or disease. (P.1.5, P.4.7, P.5.1, P.5.3, P.5.4, P.6.10)**MS-4** Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. (P.1.1, P.1.2, P.2.6, P.6.5)

PLO P Integrated functions and Special Environments			
At the end of an introductory one-semester physiology course, a student should be able to do the following:		Core Concepts	Skills
P-1 Thermoregulation			
P.1.1	Diagram or describe thermal balance for the body, including sources of heat production (e.g., metabolism, exercise, shivering) and heat loss (e.g., convection, conduction, radiation, and evaporation).	CC.3.3, CC.4.2 CC.4.7, CC.4.8 CC.6.3	MS-4
P.1.2	Define <i>thermoregulatory set point</i> and diagram or describe the negative feedback control of body core temperature homeostasis, including the role of the hypothalamic thermoregulatory set point.	CC.2.3	MS-4
P.1.3	Describe the regulatory mechanisms used for body temperature homeostasis (e.g., sweating, shivering, behavioral responses).	CC.2.5 CC.6.3	
P.1.4*	Predict the physiological consequences of a prolonged and/or extremely high body temperature (e.g., fever, heat stroke).	CC.2.10 CC.6.6	PS-1
P.1.5*	Identify the mechanisms for attempting to maintain thermal balance while walking in extreme heat (temperature is 49°C/120°F) and cold (temperature is 0°C/32°F).	CC.6.3	
P-2 Exercise Physiology			
P.2.1	Define <i>exercise</i> and V_{O2max} .		
P.2.2	Predict the physiological changes for the following when a person transitions from rest to 25% and to 95% of maximal exertion: ventilation rate, cardiac output (CO), total peripheral resistance (TPR), systolic arterial pressure, diastolic arterial pressure, and mean arterial pressure (MAP).	CC.2.4, CC.2.5 CC.6.6	PS-4
P.2.3	Predict the physiological changes in arterial and venous blood gas concentrations from rest to 25% and to 95% of maximal exertion.	CC.6.6	PS-4
P.2.4	Compare and contrast the neural and local control of skeletal muscle and skin blood flow at rest and during sustained exercise.	CC.2.12	
P.2.5	Contrast the relative distribution of cardiac output (CO) to tissues (e.g., brain, skeletal muscle, digestive system) at rest and during sustained aerobic exercise.	CC.1.4	
P.2.6*	Diagram or describe the feedforward mechanism for increased ventilation at the onset of exercise when arterial blood gasses have not yet changed.	CC.2.9 CC.6.4, CC.6.5	MS-4
P.2.7*	Compare the primary substrate utilization (lipids/fat versus glucose) for ATP production at rest, at 25% of maximal exertion, and at 95% of maximal exertion.	CC.4.4, CC.4.5 CC.4.8	

P.2.8*	Compare the capacity for sustained exercise for the following energy processes: muscle phosphocreatine utilization, anaerobic muscle glycolysis, and aerobic muscle glucose metabolism.	CC.4.2, CC.4.4 CC.4.5	
P.2.9*	Describe how exercise alters insulin secretion and the mechanism of glucose entry into skeletal muscle cells.	CC.6.5	
P.2.10*	Describe the benefits of exercise for an individual with chronically elevated blood glucose levels.		
P.2.11*	Evaluate evidence on the health benefits of exercise training to the cardiovascular, musculoskeletal, endocrine, immune, and nervous systems.	CC.6.2	PS-1
P-3 Integrated Control of Stress			
P.3.1	Describe the general adaptation syndrome (GAS) in response to stress.	CC.6.4 CC.6.5	
P.3.2	Describe, compare and contrast the roles of the nervous, endocrine, and immune systems in mediating the short-term (acute) and long-term (chronic) stress responses.	CC.6.4	
P.3.3*	Describe the physiological consequences of long-term (chronic) stress.	CC.6.4 CC.6.5	
P.3.4*	Define <i>psychoneuroimmunology</i> , and explain how the nervous, endocrine, and immune systems communicate and coordinate with each other to influence physiological function and behavior.	CC.6.4	
P-4 Physiology of Extreme Environments *			
	High altitude		
P.4.1*	Describe the integrated responses of the cardiovascular, hematological, respiratory, and renal systems immediately upon arrival at high altitude (e.g., 8,000 ft above sea level) from sea level.	CC.2.5, CC.6.1 CC.6.3	
P.4.2*	Compare and contrast the integrated responses of the cardiovascular, hematological, respiratory, and renal systems immediately upon arrival at high altitude (e.g., 8,000 ft above sea level) from sea level to integrated responses after remaining at altitude for two weeks.	CC.2.5, CC.6.1 CC.6.3	
P.4.3*	Predict long-term adaptations to high altitude (e.g., 8,000 ft above sea level) observed in populations living at high altitude (e.g., Tibetan sherpas, Andeans).	CC.6.3 CC.6.5	PS-1
	Diving		
P.4.4*	Define and describe the <i>mammalian diving reflex</i> observed in diving birds, diving mammals, and some humans.		

P.4.5*	Explain how ambient pressure changes when diving (1 atm increase for each 10 meters of depth) affect the partial pressures of inspired gases, the partial pressures of gases dissolved in plasma, hemoglobin saturation with oxygen, and ventilation.		QR-5
	Space		
P.4.6*	Describe the integrated responses of the cardiovascular, hematological, respiratory, and renal systems immediately upon arrival at the space station (microgravity).	CC.2.5, CC.6.4 CC.6.6	
P.4.7*	Compare and contrast the integrated responses of the bone, muscle, cardiovascular, hematological, respiratory, reproductive, and renal systems immediately upon arrival at the space station (microgravity) <i>versus</i> after remaining in space for two months.	CC.2.5, CC.6.4 CC.6.6	MS-3
P.4.8*	Predict long-term physiological consequences to space observed in individuals living in space (e.g., International Space Station workers).	CC.6.4 CC.6.6	PS-1
P.4.9*	Apply knowledge of adaptation to microgravity to explain why astronauts returning to earth from space experience orthostatic hypotension (low blood pressure on standing).	CC.6.3 CC.6.6	PS-1
	P-5 Integrated Response to SARS-CoV-2 and COVID-19*		
P.5.1*	Explain how COVID-19 infection of type II alveolar cells can result in pulmonary edema.	CC.1.9, CC.1.12	MS-3
P.5.2*	Explain how extracellular SARS-CoV-2 viruses enter cells using the ACE-2 enzyme of the cell.	CC.1.11 CC.1.18	
P.5.3*	Given that ACE-2 converts angiotensin II to a less active form, predict how removal of ACE-2 from the cell surface as a result of SARS-CoV-2 virus binding might affect blood pressure.	CC.1.19 CC.6.5, CC.6.6	MS-3
P.5.4*	Given that SARS-CoV-2 infection causes loss of taste and smell in some people, speculate on where the virus may damage these sensory pathways.		MS-3
	P-6 Integrated Physiological Functions		
P.6.1	Describe the significance and roles of the pancreas in the function of endocrine, gastrointestinal, and muscle systems, and in metabolism.	CC.6.2	
P.6.2	Describe the significance and roles of bone in the function of endocrine, immune, and musculoskeletal systems.	CC.6.2	
P.6.3	Describe the significance and roles of the anatomical lymphatic system in the function of immune, gastrointestinal, and cardiovascular systems.	CC.6.2	

P.6.4	Describe the significance and roles of adipose tissue in the function of body systems (e.g., endocrine, digestive) and metabolism.	CC.6.2	
P.6.5	Diagram or describe the flow of information through a presynaptic neuron from its dendrites to the response of the postsynaptic cell (e.g., skeletal muscle, gland).	CC.5.1, CC.5.2 CC.5.3, CC.5.4	MS-4
P.6.6	List and describe two examples of tissues that have autorhythmic (pacemaker) activity and relate the autorhythmic activity to organ function.	CC.2.7	
P.6.7	Compare and contrast the sources and functions of calcium in skeletal, cardiac, and smooth muscle contraction.	CC.1.11 CC.1.18 CC.1.20	
P.6.8	List and describe at least three examples of cells or tissues that have the enzyme NCC-K-ATPase and explain the important functional roles of NCC-K-ATPase in those tissues.	CC.1.9 CC.1.13 CC.2.6	
P.6.9	List and describe examples of cells or tissues that have the enzyme carbonic anhydrase (CA), and explain the important functional roles of CA in those tissues (e.g., RBCs, respiratory, renal, CNS).	CC.1.9 CC.1.13 CC.2.6	
P.6.10	Applying knowledge of the nervous system, and given a specific organ/tissue, predict the division of the nervous system that controls the target, the neurotransmitter, and neurotransmitter receptor(s).	CC.2.12 CC.5.2 CC.5.3, CC.5.4	MS-3
P.6.11*	Applying knowledge of the nervous and cardiovascular systems, explain the mechanism by which nicotine from tobacco increases blood pressure.	CC.6.3 CC.6.5	PS-1
P.6.12	Describe three categories of abnormal physiological response that lead to pathology (i.e., overactive response, lack of response, inappropriate response) and list examples (e.g., in the immune system, endocrine system).	CC.6.6	
P.6.13*	Compare and contrast the hormone half-lives and secretion mechanisms for insulin and glucagon versus growth hormone.	CC.1.16 CC.1.17	
P.6.14	Describe the significance and roles of the liver in metabolism, digestive function, and clearance of substances from the blood, particularly aged erythrocytes, alcohol, and drugs.	CC.6.2	

MODULE P Integrated functions and Special Environments

BACKGROUND BASICS from other modules.

The topics in this module are so broad and varied that we are not attempting to list related material except from the Entering Competencies and Modules A *Cell Physiology & Membrane Processes* and Module B *Cell-Cell Communication & Control Systems*.

Students need to understand and be able to apply these introductory concepts in order to be successful in this module.

Entering Competencies

EC-2 Biological energy (EC.2.1, EC.2.5, EC.2.6, EC.2.7)

EC-5 Biological reactions (EC.5.2, EC.5.7)

EC-10 Cellular respiration (EC.10.1, EC.10.2, EC.10.3)

Module A Cell Physiology & Membrane Processes

A-3 Body fluid compartments (A.3.2, A.3.3, A.3.4, A.3.5)

A-5 Water movement across membranes (A.5.1, A.5.3)

A-6 Osmolarity & tonicity (A.6.2*, A.6.3, A.6.9, A.6.10*)

A-7 Membrane potential differences (A.7.1, A.7.4, A.7.5, A.7.7, A.7.10)

Module B Cell-Cell Communication & Control Systems

B-1 Cell-to-cell communication (B.1.3, B.1.5, B.1.6, B.1.8*)

B-2 Chemical signaling pathways (B.2.4, B.2.5, B.2.6, B.2.9, B.2.11, B.2.15, B.2.16)

Core Concepts Index and the Learning Outcomes that map to them

Skills Index and the Skills that map to them

CC-1 Structure-Function Relationships		
	Anatomy and levels of organization	Module Key
CC.1.1	Describe, in order from simplest to most complex, the major levels of organization in the body, and list examples of each.	<i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
CC.1.2	List the physiological systems of the human body, their major components, and the major functions of each.	
	C.1.1 E.1.1, E.1.2, E.1.4, E.2.1, E.3.1, E.3.3, E.3.4, E.3.5, E.3.6, E.3.7, E.4.2, E.4.3, E.4.4, E.6.1, E.7.1, E.7.5, E.7.8, E.8.1, E.8.2, E.8.3, E.9.1, E.9.5, E.9.6, E.9.11, F.1.4, F.1.5, F.2.1, F.2.3, F.2.4, F.2.5, F.3.1 G.1.1 I.1.1, J.1.1 J.2.1, J.2.2, L.2.1 L.6.3, L.6.8, L.7.1 N.1.2, N.2.5, N.3.5 O.1.2	
CC.1.3	Describe, compare and contrast the general features and functions of the four major tissue types (muscle, connective, neural, and epithelial).	
	C.1.3, C.2.1, C.2.2, C.6.2 D.1.5 E.2.1 F.1.1, F.1.2, F.1.3, F.3.1 G.1.5, G.2.5, G.2.6, G.2.7 I.8.4 L.1.5	
CC.1.4	Describe, compare and contrast epithelial tissues based on structural characteristics and function, and give an example and location of each type.	
	A.4.1, A.4.2, A.4.3, A.4.6, A.4.7 E.2.3 I.1.7, I.1.9 J.3.1, J.3.3, J.4.4, J.4.7 L.1.5, L.6.3, L.6.15, L.6.19	
CC.1.5	Compare and contrast the structure and function of exocrine and endocrine glands.	
	C.1.2, C.3.1, C.3.2, C.5.10, C.6.1 I.1.7, I.1.9 L.4.4, L.5.4, L.6.8, L.6.9 M.4.2	

CC.1.6	Apply the concepts of agonists and antagonists across levels of organization in the body.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	A.2.6 B.1.4, B.2.10 C.1.8, C.1.12, C.2.6, C.4.1, C.5.25, C.5.28 E.4.5 F.1.6 G.3.12, G.3.13, G.3.14, G.6.13, G.8.6 K.10.4 M.4.3	
CC.1.7	Apply the concepts of convergence and divergence across levels of organization in the body.	
	C.6.19, C.6.19 D.4.1 E.1.8, E.6.7 G.1.6, G.1.7, G.2.4 H.5.3 I.1.6, I.1.8	
Compartmentation		
CC.1.8	Define <i>compartmentation</i> and describe examples of compartments in the body across levels of organization.	
	A.1.1, A.2.1, A.3.1, A.3.2, A.3.4, A.3.6, A.6.3, A.6.9 D.1.1, D.3.10, D.4.3 E.2.2, E.7.2, E.9.6, E.9.7, E.9.9 F.1.4, F.1.5, F.3.5 H.1.1 I.1.2 J.1.1, J.1.3, J.1.4, J.3.1 L.1.3, L.5.2, L.6.2, L.7.1, L.7.3, L.8.1, L.8.4, L.9.1 N.2.12	
CC.1.9	Explain the adaptive advantages and challenges of compartmentation in the body .	
	A.2.4, A.2.5, A.2.8, A.2.9, A.2.10, A.2.11, A.3.2, A.4.2, A.4.4, A.6.3 B.2.1 C.2.4, C.2.7, C.3.2, C.3.4, C.3.8, C.5.2, C.5.7, C.6.7 D.1.9, D.1.5 E.2.2, E.2.4, E.2.5 G.4.5, G.6.7 I.1.4 K.8.3, K.9.6 L.1.3, L.6.37 P.5.1, P.6.8, P.6.9	

CC.1.10	Compare and contrast the ways different compartments in the body are distinguished from each other.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	A.3.5, A.6.2, A.6.6, A.6.7, A.6.8, A.6.9, A.7.1 C.6.4, C.1.10 D.1.5, D.1.6 E.2.2, E.2.4 G.1.3, G.1.8, G.1.9, G.2.4 L.1.2, L.5.3 M.1.4 N.2.12, N.3.16 O.1.5	
CC.1.11	Compare and contrast the methods by which substances move between compartments in the body, and name an example of a compartment that has multiple routes for entry or exit.	
	A.1.1, A.2.1, A.2.4, A.2.5, A.2.9, A.2.10, A.2.11, A.4.4, A.4.5, A.6.3 C.2.4, C.2.7, C.5.2, C.5.3, C.5.4, C.5.7 D.1.1 E.2.2, E.2.3, E.2.4 F.3.5 G.2.3, G.9.2 I.1.2, I.1.10, I.5.6, I.7.1, I.8.4, I.8.5 J.1.5, J.2.3, J.2.4, J.2.8, J.3.3, J.4.3, J.4.17 K.1.1, K.1.5, K.2.3, K.2.4, K.3.1, K.3.2, K.4.1, K.5.3, K.8.4, K.8.11, K.8.12, K.8.13, K.8.14, K.8.15, K.9.3, K.9.6 L.2.2, L.2.7, L.4.7, L.5.5, L.6.20, L.6.26, L.6.27, L.6.28, L.6.35, L.6.36, L.6.39, L.6.40, L.6.43, L.6.44, L.6.45, L.6.46, L.7.5, L.7.6, L.9.6 N.3.2, N.5.3 O.3.4 P.2.9, P.5.2, P.6.7	
CC.1.12	Describe how changes in the size or shape of a structure alter the surface-to-volume ratio of the structure, and list biological examples of how modifications in surface area change the surface-to-volume ratio (e.g., microvilli on the surface of a cell).	
	A.2.3 D.1.1 G.7.9, G.7.10, G.7.11 H.2.1 I.1.8 L.1.4, L.4.3, L.6.6, L.6.19	

Mass balance and energy balance		
CC.1.13	Explain the impact of rates of inflow and outflow on the load of mass or amount of energy in a compartment.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	A.2.4, A.2.8, A.2.10, A.2.13, A.3.2 C.3.4 F.3.5 H.2.8 K.1.1, K.1.3, K.1.6, K.2.1, K.3.5, K.4.3, K.8.10, K.9.6 L.2.3, L.2.4, L.6.4, L.6.5, L.6.29, L.8.3, L.9.1 M.1.3, M.3.1, M.5.1 P.1.1	
CC.1.14	Relate the law of conservation of mass or conservation of energy to inflow, outflow, and storage of mass or energy.	
	A.3.8 B.2.5 C.1.14, C.1.14, C.1.15, C.1.16, C.3.7, C.5.3, C.5.7, C.5.26 H.2.4, H.2.5 I.1.2 J.2.5, J.4.10, J.4.11 K.1.6, L.2.3 L.7.4 M.1.3, M.3.1	
Molecular structure and function		
CC.1.15	Explain how the four major classes of biomolecules can combine to form complex molecules.	
	A.1.2 C.3.3, C.5.11, C.6.5 L.6.21, L.6.31	
CC.1.16	Describe the relationship between molecular structure and function.	
	A.1.2, A.2.1, A.2.2, A.2.3, A.2.5, A.2.7, A.2.8, A.2.10, A.2.11 B.2.14 D.3.5, D.3.7, D.3.21, D.4.9 E.3.2 F.2.2, F.2.6, F.2.7, F.3.2, F.5.4 H.2.3 I.1.8 K.2.4 L.5.10 P.6.13	

CC.1.17	Explain how the properties of molecules influence their interactions with each other and with ions.	
	A.2.1, A.2.8 B.2.4, B.2.14 C.1.8, C.1.9, C.1.13, C.1.16, C.3.7, C.3.8, C.5.11, C.5.18, C.5.22, C.6.6, C.6.16 D.1.8 F.2.2, F.2.7, F.3.2 I.3.2, I.7.7, I.7.8, I.7.9, I.7.11, I.7.13, I.7.14 K.8.2 L.6.17, L.6.18, L.6.23, L.6.24, L.6.25	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
CC.1.18	Explain factors that influence the specificity and affinity of protein-ligand interactions.	
	A.1.1 B.2.1, B.2.2, B.2.4, B.2.6, B.2.7 C.1.8, C.1.13, C.3.9, C.6.18, C.6.19, C.6.20 D.1.3, D.1.7 F.2.2 H.6.2 I.7.7, I.7.8, I.7.9 J.4.3, J.4.24, J.4.25 K.5.3, K.8.2 P.5.2, P.6.7	
CC.1.19	Describe multiple physiological processes that involve proteins binding to ligands.	
	A.2.6 B.2.6, B.2.7 D.1.7, D.4.5 F.3.2 H.6.3, H.6.4 I.1.7, I.8.2, I.8.5, I.8.6, I.8.7 J.4.3, L.6.18, L.6.25 O.2.3, O.2.4, O.2.7, O.3.2, O.4.2, O.6.1 P.5.3, P.6.8, P.6.9, P.6.13	
CC.1.20	Explain the concept of saturation of protein binding sites and describe how saturation can influence the rate of a physiological process.	
	A.2.6 B.2.3, B.2.7 D.4.6 I.7.2, I.7.3, I.7.4, I.7.5, I.7.6, I.7.7, I.7.8, I.7.12, I.7.13, I.7.14 J.4.16, J.4.19, J.4.20, J.4.21, J.4.22, J.4.23	

CC.1.21	Describe how the quantity of binding sites and relative ligand concentration relate to the saturation of protein binding sites and provide an example.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	A.2.6 B.2.3, B.2.7 D.1.7 I.7.3, I.7.6, I.7.11, I.7.12, I.7.13 J.4.19, J.4.20, J.4.21, J.4.22, J.4.23	
CC.1.22	Describe physiological or pharmacological examples of molecular competition.	
	A.2.6 B.2.3, B.2.7 D.4.6 I.7.13 J.4.16, J.4.24, J.4.25	
Properties of physical systems		
CC.1.23	Describe and explain the reciprocal (inverse) relationship between elastance and compliance.	
	F.4.7 G.6.7, G.6.8, G.7.17, G.8.10, G.10.3 I.3.1, I.3.5	
CC.1.24	Describe the impact of a lever system on the amplification of force, and describe an example.	
	F.1.7, F.2.6	
CC.1.25	Describe and explain the impact of viscosity on fluid flow.	
	G.7.3, G.7.12 I.2.6	
CC.1.26	Explain the relationship between pressure and volume for a compressible fluid (e.g., air) versus a noncompressible fluid (e.g., water).	
	G.5.9, G.5.10, G.5.11, G.8.2, G.8.3, G.8.5 I.2.4, I.2.5, I.2.7, I.2.12	
CC.1.27	Describe how structures can be linked together mechanically at different levels of organization (e.g., protein-protein interactions, cell-cell junctions, tendons between muscles and bone).	
	A.4.1 F.2.6 G.4.1, G.4.2, G.4.3, G.6.3 I.2.8 J.1.3, J.3.2, J.3.4, J.3.15	

CC-2 Homeostasis and Control Pathways		
	Homeostasis	Module Key
CC.2.1	Define homeostasis, and explain its importance for body function.	<i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	A.2.2 C.5.5, C.5.6, C.5.8, C.5.13 H.2.4, H.2.8 K.1.2, K.2.1, K.4.2, K.8.1	
CC.2.2	Distinguish between equilibrium and steady state, then explain and give an example of how a system can be a steady-state disequilibrium.	
	A.7.1., A.7.2, A.7.3, A.7.4, A.7.5, A.7.7, A.7.11, A.7.13, A.7.14 I.5.4, I.8.1 K.8.6, K.8.7	
CC.2.3	Explain the roles of the following in maintaining body homeostasis: setpoint and acceptable range, regulated (monitored) variable, controlled variable, negative feedback.	
	C.5.5 E.6.2 G.8.8 I.9.2, I.9.4 K.4.2 P.1.2	
CC.2.4	List physiological variables for which the body attempts to maintain homeostasis and variables that are not subject to homeostatic regulation, then explain why each variable belongs in the given category.	
	C.5.5 G.8.8 H.5.1, H.5.6 I.6.1, I.6.2, I.9.3, I.10.1 J.3.14, J.3.16, J.6.3 K.3.3 L.3.2 P.2.2	
CC.2.5	Distinguish between a regulated and controlled variable by describing a generalized model of a process subject to homeostatic regulation.	
	G.8.8, G.8.9 I.9.3 K.2.5, K.3.3, K.3.4, K.8.9 P.1.3, P.2.2, P.4.1, P.4.2, P.4.6, P.4.7	

CC.2.6	Explain how the principle of mass balance and homeostasis are interrelated, and describe an example in the body.	
	C.5.6, C.5.8, C.5.9 G.9.9 I.5.6, I.8.4 J.4.21, J.4.23 K.1.2, K.1.3, K.2.1, K.3.3, K.3.4, K.4.2, K.7.2, K.7.4, K.7.5, K.7.6, K.7.7, K.7.8, K.7.9, K.7.10, K.8.6, K.8.9, K.8.13, K.8.14, K.8.15, K.9.3, K.9.4 L.5.9 M.4.9	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
CC.2.7	Describe physiological processes or parameters that cycle in a predictable fashion over a period of time.	
	C.1.5, C.6.10 E.5.6 G.4.9, G.5.2, G.5.8, G.5.9, G.5.10 I.2.7, I.9.1 L.2.6, L.2.8, L.9.4 N.3.9, N.3.10, N.3.11, N.3.12, N.3.13, N.3.19, N.3.20, N.3.24 P.6.6	
	Control pathways	
CC.2.8	List the steps of a physiological reflex from stimulus to response using a control system model (i.e., input, control center, output).	
	B.1.5, B.1.8, B.2.14 C.1.6, C.1.17, C.1.18, C.1.19, C.2.5, C.2.6, C.3.5, C.3.9, C.4.1, C.4.2, C.4.3, C.4.4, C.5.14, C.5.15, C.5.27, C.6.3, C.6.7, C.6.8, C.6.9 E.1.5, E.4.1 G.8.8 H.2.7, H.5.1 I.9.3, I.9.7 K.2.2, K.3.6, K.4.4, K.5.1, K.5.2, K.6.1, K.7.3, K.8.9 L.3.1, L.7.8 M.4.5, M.4.6, M.4.7 N.2.7, N.3.6, N.9.1	
CC.2.9	Compare and contrast negative feedback, positive feedback, and feedforward in terms of the relationship between stimulus and response, and describe examples of each.	
	C.1.6, C.1.11, C.1.17, C.1.18, C.1.19, C.2.5, C.2.8, C.3.6, C.3.11, C.3.12, C.3.13, C.5.14, C.6.3 D.3.9 G.8.9 H.5.6 L.4.2, L.6.5 M.4.5 N.2.7, N.3.6, N.3.18 P.2.6	

CC.2.10	Predict outcome(s) when a response pathway is altered or disrupted.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	B.2.15, B.2.16 C.1.7, C.1.9, C.1.10, C.1.12, C.3.10, C.3.11, C.3.12, C.3.13, C.4.6, C.5.16, C.5.17, C.5.20, C.5.29, C.6.12, C.6.13, C.6.20 D.3.17, D.3.20, D.3.21, D.4.10, D.5.1 E.6.12, E.10.1, E.10.2 F.4.4, F.7.1 G.3.3, G.3.14, G.4.3, G.4.10, G.10.4 H.2.9, H.5.8, H.5.9 I.2.15, I.2.16, I.3.5, I.5.7, I.6.3, I.6.4, I.6.5, I.7.11, I.7.12, I.7.13, I.9.4, I.10.2 J.6.1 K.2.5, K.4.2, K.7.2, K.8.8, K.10.1, K.10.2, K.10.3, K.10.4 L.6.16, L.6.34, L.9.5, L.9.9 M.4.11, M.4.12, M.5.3 N.2.10, N.9.2, N.9.3, N.9.8, N.9.10 O.8.1, O.8.2 P.1.4	
CC.2.11	Given a change in the response of a pathway, predict which component(s) of the pathway may have been altered or disrupted.	
	C.1.7, C.1.10, C.1.12, C.3.10, C.3.11, C.3.12, C.3.13, C.4.6, C.5.16, C.5.17, C.5.20, C.5.29, C.6.12, C.6.13, C.6.20 D.5.2 E.10.3 F.7.2 G.10.2 I.9.5, I.10.3 J.6.2 K.9.5 L.9.10 M.5.4 N.3.23, N.9.6, N.9.11	
CC.2.12	Apply knowledge of the steps of a physiological reflex to the components of a given example, then determine if the reflex is associated with the maintenance of homeostasis.	
	C.2.5, C.3.5, C.3.6, C.4.1, C.4.3, C.4.4, C.6.3, C.6.8, C.6.9 E.5.2, E.5.3, E.5.4 G.8.8 I.9.3 J.5.2 K.2.2, K.5.1, K.6.2 L.3.4, L.9.3 M.4.3 N.2.9, N.2.13, N.3.8, N.3.12, N.3.18, N.3.24, N.5.1, N.5.2, N.8.4, N.8.6 P.2.4, P.6.10	

CC-3 Gradients and Flow		Module Key
CC.3.1	Describe how a gradient determines flow between two regions, and give examples of concentration, osmotic, pressure, or electrical gradients that exist across levels of organization in the body.	<i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	A.2.3, A.2.8, A.2.11, A.4.8, A.5.1, A.5.2, A.5.3, A.6.3, A.6.7, A.6.10, A.7.14 D.1.3, D.2.1, D.3.4, D.3.14, D.3.15, D.3.17, D.3.18, D.3.19, D.4.8, D.4.11 G.5.3, G.7.1, G.7.2, G.7.6 I.1.2, I.1.10, I.2.5, I.2.6, I.2.7, I.5.5, I.5.6 J.3.6, J.3.7, J.3.8, J.3.9, J.3.10 K.1.4, K.1.5	
CC.3.2	Distinguish between velocity of flow and rate of flow (flux), and state representative units of each.	
	D.3.17 G.7.8, G.7.10, G.7.11 I.3.3	
CC.3.3	Predict how changes in a gradient will affect flow along the gradient.	
	A.2.3, A.4.8, A.6.3, A.6.7, A.6.10, A.7.14 D.1.3, D.2.4, D.3.4, D.3.6, D.3.11, D.3.13, D.3.15 G.5.4, G.5.7, G.7.5, G.7.6, G.7.7, G.7.13, G.7.29, G.9.10 I.2.7, I.4.4 J.3.6, J.3.13 K.1.3, K.1.4, K.4.3 P.1.1, P.3.3, P.4.5	
CC.3.4	Predict how differences in resistance will affect flow .	
	D.2.1, D.2.4, D.3.2, D.3.4, D.3.6, D.3.8, D.3.14, D.3.15, D.3.17, D.3.18, D.3.19 G.7.3, G.7.4, G.7.5, G.7.7, G.7.10, G.7.20, G.7.21, G.8.6, G.9.10 I.1.5, I.2.6, I.3.3, I.3.4, I.3.6, I.3.7, I.4.5 J.3.13, J.3.17 P.2.5, P.5.1	
CC.3.5	Predict the direction and magnitude of flow in the presence of two opposing gradients .	
	D.3.14 G.8.4, G.9.4, G.9.5, G.9.8, G.9.10 I.1.10 J.3.7, J.3.9, J.3.10	

CC-4 Energy Types, Storage, Use and Conversion		
CC.4.1	Compare and contrast physiologically relevant forms of energy .	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	A.7.10 M.2.6	
CC.4.2	Identify and list biological examples in which energy is converted from one form to another.	
	A.1.1, A.2.4, A.2.8, A.2.9, A.4.5, A.4.7, A.7.10 E.7.6, E.7.8, E.9.3, E.9.6, E.9.7 F.2.8 M.2.6, M.2.7, M.2.8, M.2.9, M.2.10, M.3.1 P.1.1, P.2.8	
CC.4.3	Compare and contrast different forms of biological work and provide examples.	
	A.2.11 I.3.7 P.4.3	
CC.4.4	Compare and contrast the forms of short-term and long-term energy storage in the body.	
	M.1.4, M.2.5, M.2.7, M.2.8, M.2.9, M.2.10 P.2.7, P.2.8	
CC.4.5	Compare and contrast the relative amounts of chemical bond energy stored in different molecules .	
	F.5.1, F.5.2, F.5.3 M.1.5, M.1.6, M.1.7, M.2.6 P.2.7, P.2.8	
CC.4.6	Explain the relationship between the magnitude of a concentration, osmotic, pressure, or electrical gradient and the potential energy stored in that gradient .	
	A.2.3, A.2.4, A.2.8, A.7.12 J.4.5, J.4.6	
CC.4.7	Describe processes that require energy in the body across all levels of organization.	
	A.2.4, A.2.8, A.2.9, A.2.11, A.4.5, A.4.7, A.7.10 B.2.9 C.5.4 F.2.6, F.2.8, F.5.3, F.6.6 G.3.5 J.4.4, J.4.5, J.4.6, J.4.7, J.4.16, J.4.17 K.3.6, K.4.7, K.5.3 M.2.3, M.2.10 P.1.1	
CC.4.8	Explain what is meant by <i>the efficiency of a biochemical reaction</i> and list examples of its importance in physiology.	
	M.2.6, M.3.1, M.3.3 P.1.1, P.4.8	

CC-5 Communication		
CC.5.1	Explain the importance of coordinated communication of information in the body.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	B.1.1, B.1.2, B.1.3 D.1.2, D.3.20, D.4.10, D.4.11, D.3.16 E.1.7, E.1.9, E.2.5, E.4.1, E.4.5, E.5.7, E.5.8, E.6.10, E.7.9, E.7.10 F.3.2, F.3.3 G.3.8, G.4.2, G.7.23, G.7.24 H.5.2, H.5.3, H.5.5 I.9.4, I.9.2 K.7.1-K.7.10, K.8.9, K.9.3 L.3.2, L.3.3, L.5.11 M.3.5, M.4.1, M.4.3, M.5.1 N.1.4, N.3.8, N.3.12, N.3.24, N.7.3, N.7.4, N.7.5 O.2.5, O.7.1 P.6.5	
CC.5.2	Define <i>transduction</i> and explain its role in communication.	
	A.1.1 B.1.1, B.1.2, B.1.3, B.2.8, B.2.9, B.2.12, B.2.13 C.1.7 D.1.7, D.1.9, D.1.12, D.4.2, D.4.11 E.6.3, E.6.4, E.6.15, E.7.7, E.8.2, E.8.3, E.8.4, E.8.5, E.9.2, E.9.6, E.9.7 F.3.3 P.6.5, P.6.10	
CC.5.3	Explain different ways information is coded to serve unique functions.	
	A.7.15 B.1.1, B.1.2, B.1.3, B.2.1 D.2.1, D.2.4, D.3.2, D.3.11 E.5.5, E.5.7, E.5.8, E.6.4, E.6.5, E.6.6, E.6.8, E.6.10, E.6.11, E.6.13, E.6.14, E.6.15, E.9.4 F.3.4 G.3.5, G.3.6 H.6.1 P.6.5, P.6.10	
CC.5.4	Explain how information can be converted from one form to another.	
	A.1.1, A.2.7, A.7.15 B.1.1, B.1.2, B.1.3, B.1.5 D.2.1, D.2.3, D.3.1, D.3.11, D.3.12, D.4.4 E.6.3, E.6.4, E.8.2, E.8.3, E.8.4, E.8.5 F.3.3 P.6.5, P.6.10	

CC-6 Systems Integration		
CC.6.1	Define integration of function within and across physiological systems at all levels of organization.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	C.4.5 I.1.2 K.7.3, K.9.4 L.3.2, L.3.4, L.4.2, L.5.7, L.8.2, L.9.2, L.9.7 M.2.5, M.4.1, M.4.3, M.4.8, M.4.9 N.2.9 O.2.5, O.4.6 P.4.1, P.4.2	
CC.6.2	Describe how one body structure can participate in or regulate the function of multiple body systems .	
	B.1.6 L.6.10 M.6.2, M.4.4, M.4.6 N.5.4 P.2.11, P.6.1, P.6.2, P.6.3, P.6.4, P.6.14	
CC.6.3	Explain how multiple organ systems can work together to maintain homeostasis .	
	B.1.6 C.6.3, C.5.8 I.9.4 J.6.3 K.2.1, K.2.2, K.3.3, K.4.4, K.5.1, K.7.3, K.7.4, K.7.5, K.7.6, K.7.7, K.7.8, K.7.9, K.7.10, K.8.4 K.9.4 L.6.13 M.2.5, M.4.10 P.1.1, P.1.3, P.1.5, P.2.6, P.3.2, P.4.1, P.4.2, P.4.3, P.4.9	
CC.6.4	Explain how multiple organ systems can work together in non-homeostatic processes .	
	C.4.5 F.3.1 I.1.2 L.7.7 N.2.9, N.4.2, N.4.4, N.4.6 P.3.2, P.3.3, P.3.4, P.4.6, P.4.7, P.4.8	
CC.6.5	Describe how change in one organ system can affect the functioning of other organ systems .	
	C.1.8, C.4.5 F.6.5, F.7.2 H.7.1 J.6.3 K.2.5, K.6.5, K.5.4, K.7.1, K.8.8, K.9.2, K.9.4, K.10.5 P.2.6, P.2.9, P.3.1, P.3.3, P.4.3, P.6.11	

CC.6.6	Apply physiological knowledge to predict outcomes when system integration is altered or disrupted.	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
	C.1.9, C.1.10, C.5.17, C.6.13, C.6.20 D.5.1, D.5.2 E.10.1, E.10.2 F.7.1, F.7.2 G.6.11, G.6.12, G.7.18, G.8.7, G.8.9, G.10.1 I.9.5, I.9.6 J.6.1, J.6.2, J.6.3, J.6.4 K.2.5, K.2.6, K.5.4, K.7.1, K.7.4, K.7.5, K.7.6, K.7.7, K.7.8, K.7.9, K.7.10, K.9.4, K.9.5, K.10.1, K.10.2, K.10.3, K.10.4, K.10.5 L.9.9, L.9.10 M.4.12, M.5.3, M.5.4 N.3.23, N.9.3, N.9.10, N.9.11 O.8.1, O.8.2 P.1.4, P.2.2, P.2.3, P.4.6, P.4.7, P.4.8, P.4.9, P.5.3, P.6.12	

Process of Science (PS)	
PS-1 Draw conclusions based on inference and evidence-based reasoning.	Module Key
A.2.11, A.4.8, A.6.8 B.2.16 C.1.9, C.1.16, C.5.29 D.3.20, D.3.21, D.4.10, D.5.1, D.5.2 E.10.2, E.10.3 F.7.1, F.7.2 G.4.10, G.8.10, G.9.10, G.10.1, G.10.2, G.10.4, G.10.5 H.2.9, H.5.9, H.6.5 I.1.10, I.2.16, I.4.5, I.10.1, I.10.2, I.10.3 J.3.10, J.4.24, J.4.25, J.6.1, J.6.2, J.6.3, J.6.4 K.1.3, K.1.6, K.2.6, K.3.3, K.3.4, K.10.1, K.10.2, K.10.3, K.10.5 L.6.34, L.9.6, L.9.7 M.4.8, M.4.12 N.2.10, N.7.2, N.9.3 O.5.3, O.8.5 P.1.4, P.2.11, P.4.3, P.4.8, P.4.9, P.6.11	A = Cell physiology B = Control systems C = Endocrine D = Cellular neuro E = Systems neuro F = Muscle G = Cardiovascular H = Blood I = Respiratory J = Renal K = Fluid-electrolyte L = Digestive M = Metabolism N = Reproduction O = Immune P = Integrated function
PS-4 Formulate testable hypotheses, make predictions from data, and draw appropriate, evidence-based conclusions.	
A.2.10, A.6.3, A.6.10, A.7.7, A.7.12, A.7.13, A.7.14 B.2.3 C.1.6, C.1.12, C.3.10, C.4.6, C.5.16, C.5.17, C.5.20, C.6.12, C.6.13, C.6.20 D.3.13 E.4.6, E.6.12, E.10.1 G.3.3, G.3.14, G.4.3, G.7.18, G.7.21 H.6.4 I.2.15, I.6.4, I.6.5 K.9.5 P.2.2, P.2.3	
Quantitative Reasoning (QR)	
QR-2 Select and use appropriate mathematical relationships to solve problems.	
A.3.8, A.3.9, A.6.5, A.7.11 G.5.6, G.5.12, G.6.10, G.6.11, G.6.12, G.7.2, G.7.3, G.7.4, G.7.6, G.7.7, G.7.8, G.7.12, G.7.15, G.8.1, G.8.2, G.9.4 I.2.4, I.2.5, I.2.10, I.2.12, I.3.2, I.5.2 J.3.7, J.4.2, J.4.12, J.4.13, J.4.14, J.4.18 K.3.5, K.4.3, K.8.10 M.1.7	
QR-5 Create and/or interpret graphs and other quantitative representations of physiological processes.	
A.7.8 C.1.8 D.3.4 F.4.2, F.4.3, F.4.4 G.3.1, G.3.2, G.3.7, G.4.7, G.4.8, G.5.8, G.5.9, G.5.10, G.6.4, G.7.5, G.7.10 I.2.7, I.2.13, I.4.3, I.4.4, I.7.4, I.7.5, I.7.6, I.7.10, I.7.12, I.7.13, I.7.14 J.4.21, J.4.22, J.4.23 M.4.10, M.5.2 N.3.10, N.3.12, N.3.20 O.4.4, O.8.3 P.4.5	

Modeling and Simulation of Physiological Processes, Systems and Diseases (MS)	
MS-3 Use conceptual models (e.g., diagrams, concept maps, flow charts) and simulations to describe the important components of the model, summarize relationships, make predictions and refine hypotheses about a physiological process, system or disease. A.3.1, A.4.1, A.4.5, A.7.15 B.1.5, B.2.13 C.1.10, C.3.12, C.3.13 D.1.2, D.1.3, D.1.6, D.3.17, D.4.4, D.4.5, D.4.7, D.4.8 G.2.3, G.8.3, G.8.4, G.8.7, G.8.9 H.5.3, H.5.8, H.6.3 I.7.3, I.8.6, I.8.7, I.9.4 J.2.5, J.3.9, J.3.12, J.3.13, J.4.7, J.4.10, J.4.15 K.1.2, K.2.5, K.4.2, K.5.4, K.7.1, K.8.6, K.8.8, K.9.3, K.9.4, K.10.4 L.5.9, L.6.16, L.9.5, L.9.9, L.9.10 M.4.3, M.5.3, M.5.4 N.1.4, N.1.6, N.1.7, N.3.23, N.5.7, N.9.1, N.9.2, N.9.6, N.9.7, N.9.8, N.9.10, N.9.11 O.8.1, O.8.2, O.8.4 P.1.5, P.4.7, P.5.1, P.5.3, P.5.4, P.6.10	Module Key <i>A = Cell physiology</i> <i>B = Control systems</i> <i>C = Endocrine</i> <i>D = Cellular neuro</i> <i>E = Systems neuro</i> <i>F = Muscle</i> <i>G = Cardiovascular</i> <i>H = Blood</i> <i>I = Respiratory</i> <i>J = Renal</i> <i>K = Fluid-electrolyte</i> <i>L = Digestive</i> <i>M = Metabolism</i> <i>N = Reproduction</i> <i>O = Immune</i> <i>P = Integrated function</i>
MS-4 Create and revise conceptual models (e.g., diagrams, concept maps, flow charts) to propose how a physiological process or system works. A.4.7 B.2.7 C.1.18, C.3.5, C.3.6, C.4.1, C.4.3, C.5.4, C.5.14, C.5.18, C.6.8, C.6.9 D.1.1, D.2.2, D.3.3, D.4.3 E.1.5, E.1.7, E.1.8, E.5.2, E.5.3, E.5.4, E.6.7, E.6.13, E.6.14, E.7.1, E.7.2, E.7.8, E.8.2, E.9.1, E.9.5, E.9.11 F.2.1, F.2.2, F.2.3, F.2.7, F.3.1 G.4.9, G.5.2, G.8.8, G.9.2 H.5.4, H.5.6 I.8.1, I.8.2, I.8.4, I.8.5, I.9.3 J.3.6, J.4.4, J.4.5 K.2.2, K.2.4, K.5.1, K.6.1, K.7.4, K.7.5, K.7.6, K.7.7, K.7.8, K.7.9, K.7.10, K.8.7, K.8.9, K.8.12, K.8.13, K.8.14, K.8.15 L.1.3, L.1.5, L.2.3, L.3.1, L.3.2, L.4.7, L.5.7, L.5.8, L.6.6, L.6.10, L.6.11, L.6.15, L.6.18, L.6.20, L.6.25, L.6.27, L.6.28, L.6.30, L.6.35, L.6.39, L.6.43, L.6.45, L.7.1, L.7.8, L.9.2, L.9.3 M.3.1, M.4.5, M.4.7, M.4.9, M.4.11 N.2.7, N.2.12, N.2.13, N.3.5, N.3.6, N.3.9, N.3.15, N.3.18, N.3.24, N.8.4, N.8.6 P.1.1, P.1.2, P.2.6, P.6.5	