Society Learning Goals	Society Sample Learning Objectives
Foundational Concept: Energy is required and transformed in biological systems	
What is the nature of biological energy? *Many forms of energy are involved in biological processes: light, chemical, conformational, mechanical, and gradients. These forms can be understood in terms of the principles of thermodynamics. Energy is utilized for diverse purposes, such as the work required to synthesize biomolecules, create electrical and chemical gradients, perform mechanical work or stored within biomolecules.*	Compare and contrast biologically relevant forms of energy (e.g. kinetic energy versus potential energy, energy stored in bonds versus potential energy of concentration gradients).
	Identify and explain instances when energy is converted from one form to another.
	Write a general chemical reaction and the corresponding mathematical expression that approximates its equilibrium constant (K_{eq}).
	Explain the relationship between equilibrium constants and reaction rate constants
	Apply knowledge of basic chemical thermodynamics to biologically catalyzed systems.
	Account for energy changes in the intermediate steps that define a biological process and predict the spontaneity of the overall process or an intermediate step.
	Explain the properties of biomolecules with high-energy transfer potential that make them suitable as energy currency.
How do enzymes catalyze biological reactions? *Enzymes, which can be proteins or RNA, are macromolecules with catalytic functions. They do not alter reaction equilibria; instead, they lower the activation energy barrier of a particular reaction allowing it to proceed more rapidly. Key concepts of enzyme kinetics are typically defined in terms of the initial rate of product formation, $V_{o,}$ and various catalytic kinetic parameters, such as V_{max} or K_{cat} and K_m, which are either mathematically defined for enzymes that follow Michaelis-Menten kinetics or defined empirically for more complicated enzyme models.*	Identify the factors contributing to the activation energy of a reaction.
	Explain transition state stabilization.
	Calculate the rate enhancement of an enzyme-catalyzed reaction.
	Explain what a substrate is in terms of being a reactant.
	Differentiate between the activation energy, the free energy and standard free energy of a reaction.
	Use kinetic parameters to compare enzymes.
	Distinguish the different forms of catalytic inhibition and explain how and why they differ.

	Quantitatively model how catalyzed reactions occur and calculate kinetic parameters of enzymes from experimental data.
	Explain how catalytic parameters vary as one varies substrate or enzyme concentration.
	Interpret the physical meaning of various kinetic parameters and describe the underlying assumptions and conditions (such as steady state or equilibrium) on which different parameters depend
How is energy of chemical processes coupled in metabolic pathways? *Biochemical systems couple energetically unfavorable reactions with energetically favorable reactions. These reactions can be part of catabolic pathways where complex substances are broken into simpler ones with the release of energy or anabolic pathways where complex molecules are synthesized with an input of energy.*	Discuss the concept of Gibbs free energy and how to apply it to chemical transformations
	Explain how endergonic and exergonic pathways can be coupled and how this applies to metabolism.
	Calculate the overall ΔG for a coupled reaction given the ΔG values for the component reactions.
	Explain the simplifying assumptions made in biochemistry that are consistent with physiological conditions and make "biochemical standard conditions" (steady state) different from the standard conditions (equilibrium conditions) normally referred to in chemistry.
	Predict how perturbing a system affects the actual free energy (both mathematically and conceptually).
	Explain evolutionary conservation of key metabolic pathways.
	Explain differences in energy use and production in different cells and different biological systems.
	Explain the role of gene duplication in the evolution of energy production and utilization by different organisms.
Foundational Concept: Macromolecular Structure Determines Function and Regulation	
What factors contribute to the size and complexity of biological macromolecules?	Discuss the diversity and complexity of various biologically relevant macromolecules and macromolecular assemblies in terms of evolutionary fitness.

Macromolecules are made up of basic molecular units. They include the proteins (polymers of amino acids), nucleic acids (polymers of nucleotides), carbohydrates (polymers of sugars) and lipids (with a variety of modular constituents). The biosynthesis and degradation of biological macromolecules involves linear polymerization, breakdown steps (proteins, nucleic acids and lipids) and may also involve branching/debranching (carbohydrates). These processes may involve multi-protein complexes (e.g. ribosome, proteasome) with complex regulation.	Describe the basic units of the macromolecules and the types of linkages between them.
	Compare and contrast the processes involved in the biosynthesis of the major types of macromolecules (proteins, nucleic acids and carbohydrates).
	Compare and contrast the processes involved in the degradation of the major types of macromolecules (proteins, nucleic acids and carbohydrates
	Understand that proteins are made up of domains and be able to discuss how the protein families arise from duplication of a primordial gene.
What factors determine structure? *Covalent and non-covalent bonding govern the three dimensional structures of proteins and nucleic acids which impacts function. The amino acid sequences observed in nature are highly selected for biological function but do not necessarily adopt a unique folded structure. The structure (and hence function) of macromolecules is governed by foundational principles of chemistry such as: covalent bonds and polarity, bond rotations and vibrations, non-covalent interactions, the hydrophobic effect and dynamic aspects of molecular structure. The sequence (and hence structure and function) of proteins and nucleic acids can be altered by alternative splicing, mutation or chemical modification. Sequences (and hence structure and function) of macromolecules can evolve to create altered or new biological activities.*	Recognize the repeating units in biological macromolecules and be able to discuss the structural impacts of the covalent and non-covalent interactions involved.
	Discuss the composition, evolutionary change and hence structural diversity of the various types of biological macromolecules found in organisms.
	Discuss the chemical and physical relationships between composition and structure of macromolecules.
	Compare and contrast the primary, secondary, tertiary and quaternary structures of proteins and nucleic acids.
	Use various bioinformatics approaches to analyze macromolecular primary sequence and structure.
	Compare and contrast the effects of chemical modification of specific amino acids on a three dimensional structure of a protein.
	Compare and contrast the ways in which a particular macromolecule might take on new functions through evolutionary changes.
	Use various bioinformatics and computational approaches to compare primary sequences and identify the impact of conservation and/or evolutionary change on the structure

	and function of macromolecules.
	Predict the effects of mutations on the activity, structure or stability of a protein and design appropriate experiments to assess the effects of mutations.
	Propose appropriate chemical or chemical biology approaches to explore the localization and interactions of biological macromolecules.
	Discuss how mutations of a duplicated gene generate functional diversity.
	Evaluate chemical and energetic contributions to the appropriate levels of structure of the macromolecule and predict the effects of specific alterations of structure on the dynamic properties of the molecule.
How are structure and function related? *Macromolecules interact with other molecules using a variety of non-covalent interactions. The specificity and affinity of these interactions are critical to biological function. Some macromolecules catalyze chemical reactions or facilitate physical processes (e.g. molecular transport), allowing them to proceed in ambient conditions. These processes can be quantitatively described by rate laws and thermodynamic principles, (e.g. collision theory, transition state theory, rate laws and equilibria, the effects of temperature and structure and chemical reactivity, Coulomb's Law, Newton's laws of motion, energy and stability, friction, diffusion, thermodynamics, and the concept of randomness and probability).*	Use mechanistic reasoning to explain how an enzyme or ribozyme catalyzes a particular reaction.
	Discuss the basis for various types of enzyme mechanisms.
	Calculate enzymatic rates and compare these rates and relate these rates back to cellular or organismal homeostasis.
	Discuss various methods that can be used to determine affinity and stoichiometry of a ligand-macromolecule complex and relate the results to both thermodynamic and kinetic data.
	Critically assess contributions to specificity in a ligand-macromolecule complex and design experiments to both assess contributions to specificity and test hypotheses about ligand specificity in a complex
	Predict the biological and chemical effects of either mutation or ligand structural change on the affinity of binding and design appropriate experiments to test their predictions.
What is the role of noncovalent intermolecular interactions? *The interactions between macromolecules and other molecules*	Discuss the impact of specificity or affinity changes on biological function and any potential evolutionary impact.

rely on the same weak, noncovalent interactions that play the major role in stabilizing the three-dimensional structures of the macromolecules themselves. The hydrophobic effect, ionic interactions and hydrogen bonding interactions are prominent. The structural organization of interacting chemical groups in a binding site or an active site lends a high degree of specificity to these interactions. The specificity and affinity of these interactions are critical to biological function.	Discuss the various methods that can be used to determine affinity and stoichiometry for a ligand-macromolecule complex and relate the results to both thermodynamic and kinetic data
	Discuss the interactions between a variety of biological molecules (including proteins, nucleic acids, lipids, carbohydrates and small organics, etc.) and describe how these interactions impact specificity or affinity leading to changes in biological function.
	Predict the effects of either mutation or ligand structural change on the affinity of binding and design appropriate experiments to test their predictions.
	Discuss the relationship between the temperature required for denaturation (T_m) and macromolecular structure.
How is macromolecular structure dynamic? *Macromolecular structure is dynamic over a wide range of time scales, and the dynamic structural changes, large and small, are often critical for biological function. Small changes can come in the form of localized molecular vibrations that can facilitate the access of small molecules to interior portions of the macromolecule. Large conformational changes can come in the form of the motions of different macromolecular domains relative to each other to facilitate catalysis or other forms of work. Proteins can contain intrinsically unstructured domains. The lack of structure in solution may facilitate a function in which interactions must occur promiscuously with several other molecules. The dynamic structure of macromolecules enables rapid changes that impact the homeostasis of biochemical and molecular biological processes*	Discuss the time scales of various conformational effects in biological macromolecules and design appropriate experiments to investigate ligand induced changes in conformation and dynamics.
	Discuss the structural basis for the dynamic properties of macromolecules and predict the effects of changes in dynamic properties that might result from alteration of primary sequence.
	Predict whether a sequence is ordered or disordered and discuss potential roles for disordered regions of proteins.
	Critically discuss the evidence for and against the roles of dynamics in macromolecular function.
How is the biological activity of macromolecules regulated? *The biological activity of macromolecules is often regulated in one or more of a variety of hierarchical ways (e.g. inhibitors, activators, modifiers, synthesis, degradation and compartmentalization).*	Compare and contrast various mechanisms for regulating the function of a macromolecule or an enzymatic reaction or pathway.
	Discuss the advantages and disadvantages of regulating a reaction allosterically

	Discuss examples of allosteric regulation, covalent regulation and gene level alterations of macromolecular structure-function.
	Use experimental data to assess the type of regulation in response to either homotropic or heterotropic ligands on a macromolecule.
	Design a model to explain the regulation of macromolecule structure-function.
	Describe how evolution has shaped the regulation of macromolecules and processes
	Describe how changes in cellular homeostasis affect signaling and regulatory molecules and metabolic intermediates.
How is structure (and hence function) of macromolecules governed by foundational principles of chemistry and physics? *The structure (and hence function) of macromolecules is governed by the foundational principles of chemistry (including covalent bonds and polarity; bond rotations and vibrations; hydrogen bonds and non-covalent interactions; the hydrophobic effect; dynamic aspects of molecular structure; collision theory; transition state theory; rate laws and equilibria; the effects of temperature and structure and chemical reactivity) and physics (including Coulomb's Law; Newton's laws of motion; energy and stability; friction; diffusion; thermodynamics; and the concept of randomness and probability).*	Relate basic principles of rate laws and equilibria to reactions and interactions and calculate appropriate thermodynamic parameters for reactions and interactions.
	Explain how a ligand, when introduced to a solution containing a macromolecule to which it can bind, interacts with the macromolecule.
	Explain, using basic principles, the effects of temperature on an enzyme catalyzed reaction
	Discuss the dynamic properties of a macromolecule using foundational principles of physics
How are a variety of experimental and computational approaches used to observe and quantitatively measure the structure, dynamics and function of biological macromolecules? *A variety of experimental and computational approaches can be used to observe and quantitatively measure the structure,*	Propose a purification scheme for a particular molecule in a mixture given the biophysical properties of the various molecules in the mix.
	Either propose experiments that would determine the quaternary structure of a molecule or interpret data pertaining to tertiary and quaternary structure of molecules

dynamics and function of biological macromolecules. Equations can be derived from models and used to predict outcomes or analyze data. Data can be analyzed statistically to assess the correctness of the model and the reliability of the data.	Explain how computational approaches can be used to explore protein-ligand interactions and discuss how the results of such computations can be explored experimentally
	Compare and contrast the computational approaches available to propose a three dimensional structure of a macromolecule and discuss how the proposed structure could be validated experimentally.
	Analyze kinetic or binding data to derive appropriate parameters and assess the validity of the model used to describe the phenomenon.
Foundational Concept: Information storage and flow are dynamic and interactive.	
What is a genome? *A genome is an organism's complete set of DNA, including all of its genes. Each genome contains all of the information needed to build and maintain that organism. Some noncoding sequences enable our cells to produce different amounts of proteins at different times. For example, control sequences contain instructions to tell the cell how to switch genes on and off. Other noncoding sequences are part of genes but do not directly code for proteins. These are thought to help the cell generate a number of different proteins from one gene. More than half of the DNA in our genome is made up of repeated sequences, which appear to stabilize chromosomes; noncoding regions may have a role in spacing out the coding sequences so that they can be activated independently.*	Define what a genome consists of and how the information in the various genes and other sequence classes within each genome is used to store and express genetic information.
	Discuss how the genome is organized and packaged in prokaryotes and eukaryotes.
	Discuss tools used to study expression, conservation and structure of an organism at the genome level.
	Explain the role of repetitive and non-repetitive DNA and how its relative abundance varies from prokaryotes to eukaryotes.
How does the nucleotide sequence of the gene lead to biological function? *The information contained in the nucleotide sequence of a genome is organized into various elements, including coding regions, which contain three base codons coding for amino acids, which are transcribed to messenger RNA. The messenger RNA is translated to*	Explain the role of repetitive and non-repetitive DNA and how its relative abundance varies from prokaryotes to eukaryotes.
	Explain the process of gene regulation connecting how extracellular signals can result in a change of gene expression.
	Discuss how genes are organized and contrast the different approaches used in prokaryotic and eukaryotic organisms.

give the primary sequence of a protein and regulatory elements. The transcribed coding region for a given protein may contain introns and exons in eukaryotic cells. The amino acid sequence of a protein gives rise to biological function through stably folded regions and/or intrinsically disordered regions.	Explain how mRNA processing occurs and how splicing affects the diversity of gene products in eukaryotic organisms.
How do genomes transmit information from one generation to the next? *The primary concern of cell division is the maintenance of the original cell's genome. The genomic information that is stored in chromosomes must be replicated, and the duplicated genome must be separated cleanly between cells. Somatic cell lines are diploid (2n chromosome complement), and mitotic division normally results in two daughter cells, each with chromosomes and genes identical to those of the parent cell. Germline cells, called gametes, are haploid (having the haploid or the n chromosomal complement) and reproduce by meiosis.*	Explain the differences of mitosis and meiosis and relate them to the process of cellular division.
	Illustrate how DNA is replicated and genes are transmitted from one generation to the next in multiple types of organisms including bacteria, eukaryotes, viruses and retroviruses.
	Apply the concepts of segregation and independent assortment to traits inherited from parent to offspring and discuss how they increase genetic variation.
How are genomes maintained? *Throughout its lifetime, the DNA in a cell is under constant metabolic and environmental assault leading to damage. The ultraviolet (UV) component of sunlight, ionizing radiation and numerous genotoxic chemicals, including the (by)products of normal cellular metabolism (e.g. reactive oxygen species such as superoxide anions, hydroxyl radicals and hydrogen peroxide), constitute a permanent enemy to DNA integrity. Hydrolysis of nucleotide residues leaves non-instructive abasic sites. Spontaneous or induced deamination of cytosine, adenine, guanine or 5-methylcytosine converts these bases to the miscoding uracil, hypoxanthine, xanthine and thymine, respectively. Left unchecked, the resulting genomic instability initiates cancer and other age-related disorders. Inherited or acquired deficiencies in genome maintenance systems contribute significantly to the onset of cancer. Over time, DNA accumulates changes that activate proto-oncogenes and inactivate tumor-suppressor genes. Cells have evolved nucleotide- and base-excision repair mechanisms,*	State how the cell ensures high fidelity DNA replication and identify instances where the cell employs mechanism for damage repair.
	Explain what a mutation is at the molecular level, how it arises and how it could potentially affect the organism from gene expression to fitness.
	Relate how the cell cycle and genome maintenance are coordinated and how disruptions in this coordination could affect the organism.
	List events that result in genomic instability and explain how the cell responds to restore order and stability.
	Construct relationships between chromosome and cellular structures (e.g. telomere, centromeres and centrosomes) and explain how these structures are responsible for and/or involved in genomic stability.

homologous recombination, end joining, mismatch repair and telomere metabolism as mechanisms to maintain the integrity of the genome.	
Foundational Concept: Discovery requires objective measurement, quantitative analysis, and clear communication.	
What is the scientific process? *The process of science combines creative ideas, experimentation, and data analysis. Scientists develop a hypothesis, design and conduct appropriate experiments. Experimental results are analyzed and data interpreted using appropriate quantitative modeling and simulation tools.*	Accurately prepare and use reagents and perform the required experiments.
	When presented with an observation, develop a testable and falsifiable hypothesis.
	When provided with a hypothesis, identify the appropriate experimental observations and controllable variables.
	Determine averages and standard deviations to relate the significance of experimentally obtained data.
	Use equations and models to predict outcomes of experiments.
	Use appropriate equations to analyze experimental data and obtain parameters.
What skills are needed to access, comprehend and communicate science? *Scientists access, assess and use available information and present data in an appropriate context in a variety of ways at different levels.*	Identify, locate and use the primary literature.
	Use databases and bioinformatics tools.
	When provided with appropriate background information, identify consistencies and inconsistencies.
	Explain the big picture aspects of current challenges in the molecular life sciences.
	Use visual and verbal tools to explain concepts and data.
	Translate science into everyday examples.
What constitutes a scientific community of practice? *Science is interdisciplinary and relies on collaboration, effective teamwork, safety, and ethical practices.*	Explain the importance of and keep an accurate laboratory notebook.
	Given a case study, identify both scientific and societal ethical aspects.
	Explain cross-disciplinary concepts such as modularity, energy, modeling scientific phenomena, change over time and the differences between stochastic and deterministic phenomena
	Access and interpret safety information and conduct lab work

	safely and ethically.
	Give and take directions to be an effective team member.
Underlying Concept: Evolution	
What is the significance of evolution? *Evolution is genetic change within a population over time. Understanding evolutionary processes and the supporting evidence is an integral part of the molecular life sciences. It explains many present day issues, such as crop availability and pesticide resistance in agriculture, vaccine and drug development in medicine and regulatory mechanisms in cellular, developmental and behavioral biology.*	Describe evolution as genetic change in a population over time.
	Analyze preexisting and novel data and relate the findings in light of evolution.
	Relate evolution to concepts in biochemistry and molecular biology.
What are the mechanisms of evolution? *Many mechanisms may drive evolution. These include mutation, migration (gene flow), genetic drift (chance changes from generation to generation) and natural selection.*	Explain how mechanisms of evolution cause variation within a population.
	Distinguish between random and nonrandom evolutionary processes.
	Demonstrate their understanding of the mechanisms of evolution to relevant issues, such as antibiotic resistance, the occurrence of genetic disorders or cancer therapeutics.
How is natural selection a key evolutionary mechanism? *Evolution by natural selection results from differential reproductive success, where individuals with certain heritable traits are more successful. The fitness of an individual and its genotype is directly determined by its relative reproductive success. The fittest individuals will pass their genes to more offspring, driving the evolution of the population. In this way, the population becomes better-suited (adapted) to its environment. Multiple lines of evidence support evolution by natural selection, including the fossil record, homologies and direct observation in laboratory and field studies.*	Describe the process of natural selection.
	Distinguish between individual fitness and adaptation of populations.
	Explain how selection of phenotypes affects genotype transmission.
	Synthesize and evaluate supporting evidence for the theory of natural selection
What is the molecular basis of evolution? *Organismal traits are determined at the genetic and epigenetic*	Explain how cells can acquire new genetic material.

level. Molecular modifications at these levels may determine the RNA and protein expression patterns in a cell, influencing the phenotype of the organism. Genetic modifications can also arise from the acquisition of new genetic material via processes such as horizontal gene transfer, endosymbiosis and viral vector transfer. Transmission of these heritable alterations may lead to changes in the genetic composition of a population, thereby driving evolution.	Explain how mutations and epigenetic changes influence gene expression, structure and function of gene products and the fitness of an organism.
	Using genetic information, categorize organisms and establish phylogenetic relationships.
Underlying Concept: Homeostasis	
What is the biological need for homeostasis? *Biological homeostasis is the ability to maintain relative stability and function as changes occur in the internal or external environment. Organisms are viable under a relatively narrow set of conditions. As such, there is a need to tightly regulate the concentrations of metabolites and small molecules at the cellular level to ensure survival. To optimize resource use and to maintain conditions, the organism may sacrifice efficiency for robustness. Breakdown of homeostatic regulation can contribute to the cause or progression of disease or lead to cell death.*	Describe why maintenance of homeostasis is advantageous to an organism.
	Define homeostasis in a biochemical context to both scientifically trained and lay audiences.
	Describe how homeostatic pathways and mechanisms have been conserved throughout evolution
	Appraise the costs and benefits of different homeostatic mechanisms to an organism.
	Relate different environmental factors necessitating homeostasis to a specific adaptation.
How are steady state processes and homeostasis linked? *A system that is in a steady state remains constant over time, but that constant state requires continual work. A system in a steady state has a higher level of energy than its surroundings. Biochemical systems maintain homeostasis via regulation of gene expression, metabolic flux and energy transformation but are never at equilibrium.*	Explain that a system at chemical equilibrium (or just equilibrium) is stable over time, but no energy or work is required to maintain that condition.
	Apply the principles of kinetics to describe flux through biochemical pathways.
	Discuss a metabolic pathway in terms of equilibrium and Le Chatelier's principle.
	Relate the laws of thermodynamics to homeostasis and explain how the cell or organism maintains homeostasis.
	Model how perturbations to the steady state can result in changes to the homeostatic state.
	Propose how resources stored in the homeostatic state can be utilized in times of need.
How is homeostasis quantified?	Describe experiments discussing how signaling and

Multiple reactions with intricate networks of activators and inhibitors are involved in biological homeostasis. Modifications of such networks can lead to activation of previously latent metabolic pathways or even to unpredicted interactions between components of these networks. These pathways and networks can be mathematically modeled and correlated with metabolomics data and kinetic and thermodynamic parameters of individual components to quantify the effects of changing conditions related to either normal or disease states.	regulatory molecules and metabolic intermediates can be quantitated in the laboratory.
	Relate concentrations of key metabolites to steps of metabolic pathways and describe the roles they play in homeostasis.
	Calculate enzymatic rates and compare these rates and relate these rates back to cellular or organismal homeostasis.
	Explain that organismal homeostasis can be measured in multiple ways and over different time scales (seconds, minutes, hours, days and months).
	Given a metabolic network and appropriate data, predict the outcomes of changes in parameters of the system such as increased concentrations of certain intermediates or the changes in the activity of certain enzymes.
How is homeostasis controlled? *Homeostasis is maintained by a series of control mechanisms functioning at the organ, tissue or cellular level. These control mechanisms include substrate supply, activation or inhibition of individual enzymes and receptors, synthesis and degradation of enzymes, and compartmentalization. The primary components responsible for the maintenance of homeostasis can be categorized as stimulus, receptor, control center, effector and feedback mechanism.*	Discuss how chemical processes are compartmentalized in the organism, organ and the cell.
	Explain why biochemical pathways proceed through the intermediates that they do (gradual oxidation or reduction) and why pathways share intermediates
	Summarize the different levels of control (including reaction compartmentalization, gene expression, covalent modification of key enzymes, allosteric regulation of key enzymes, substrate availability and proteolytic cleavage) and relate these different levels of control to homeostasis.
	Compare the temporal aspect of different control mechanisms (e.g. how quickly phosphorylation occurs versus changes in gene expression).
	Hypothesize why and how organs evolved with specialized function in metazoans.
	Discuss different models of allosteric regulation.
	Formulate models relating changes in flux through a pathway to other pathways and overall homeostasis.
	Defend why anabolic and catabolic pathways are

	compartmentalized in the cell.
How do cells and organisms maintain homeostasis? *Homeostasis in an organism or colony of single celled organisms is regulated by secreted proteins and small molecules often functioning as signals. Homeostasis in the cell is maintained by regulation and by the exchange of materials and energy with its surroundings.*	Describe how the cell and organism store resources (both in terms of stored energy and chemical building blocks) for times of need and how they mobilize these resources.
	Integrate homeostasis from the cellular to the organismal level. In other words, students should be able to describe how a complex metazoan can have both a cellular and organismal response to maintain homeostasis.
	Compare and contrast homeostasis in different organisms.
	Describe homeostasis at the level of the cell, organism or system of organisms and hypothesize how the system would react to deviations from homeostasis.