QUESTION CATEGORIES (CHEMISTRY)

CRITICAL THINKING: Potential Categories

	Bloom's Level	*Key Words*
01	Remembering *(previously Knowledge)*	define, duplicate, list, memorize, recall, repeat
02	Understanding *(previously Comprehension)*	classify, describe, discuss, explain, identify, locate, recognize, select, paraphrase
03	Applying *(previously Application)*	choose, demonstrate, dramatize, employ, illustrate, interpret, solve, use, write
04	Analyzing *(previously Analysis)*	compare, contrast, criticize, differentiate, explain, distinguish, experiment
05	Evaluating *(previously 06: Evaluation)*	argue, defend, judge, select, value, evaluate, support
06	Creating *(previously 05: Synthesis)*	assemble, construct, create, design, develop, formulate

NOTE: Most of the multiple-choice questions are going to fall into the first two categories, given the nature of that question formet.

AP CURRICULAR REQUIREMENT:

Potential Essential Knowledge Categories

1. The chemical elements are fundamental building materials of matter, and all matter can be understood in terms of arrangements of atoms. These atoms retain their identity in chemical reactions.
A. All matter is made of atoms. There are a limited number of types of atoms; these are the elements.
1.A.1: Molecules are composed of specific combinations of atoms; different molecules are composed of combinations of different elements and of combinations of the same elements in differing amounts and proportions.
1.A.2: Chemical analysis provides a method for determining the relative number of atoms in a substance, which can be used to identify the substance or determine its purity.
1.A.3: The mole is the fundamental unit for counting numbers of particles on the macroscopic level and allows quantitative connections to be drawn between laboratory experiments, which occur at the macroscopic level, and chemical processes, which occur at the atomic level.
B. The atoms of each element have unique structures arising from interactions between electrons and nuclei.
1.B.1: The atom is composed of negatively charged electrons, which can leave the atom, and a positively charged nucleus that is made of protons and neutrons. The attraction of the electrons to the nucleus is the basis of the structure of the atom. Coulomb's Law is qualitatively useful for understanding the structure of the atom.

1.B.2: The electronic structure of the atom can be described using an electron configuration that reflects the concept of electrons in quantized energy levels or shells; the energetics of the electrons in the atom can be understood by consideration of Coulomb's Law.
C. Elements display periodicity in their properties when the elements are organized according to increasing atomic number. This periodicity can be explained by the regular variations that occur in the electronic structures of atoms. Periodicity is a useful principle for understanding properties and predicting trends in properties. Its modern-day uses range from examining the composition of materials to generating ideas for designing new materials.
1.C.1: Many properties of atoms exhibit periodic trends that are reflective of the periodicity of electronic structure.
1.C.2: The currently accepted best model of the atom is based on the quantum mechanical model.
D. Atoms are so small that they are difficult to study directly; atomic models are constructed to explain experimental data on collections of atoms.
1.D.1: As is the case with all scientific models, any model of the atom is subject to refinement and change in response to new experimental results. In that sense, an atomic model is not regarded as an exact description of the atom, but rather a theoretical construct that fits a set of experimental data.
1.D.2: An early model of the atom stated that all atoms of an element are identical. Mass spectrometry data demonstrate evidence that contradicts this early model.
1.D.3: The interaction of electromagnetic waves or light with matter is a powerful means to probe the structure of atoms and molecules, and to measure their concentration.
E. Atoms are conserved in physical and chemical processes.
1.E.1: Physical and chemical processes can be depicted symbolically; when this is done, the illustration must conserve all atoms of all types.
1.E.2: Conservation of atoms makes it possible to compute the masses of substances involved in physical and chemical processes. Chemical processes result in the formation of new substances, and the amount of these depends on the number and the types and masses of elements in the reactants, as well as the efficiency of the transformation.
2. Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules and the forces between them.
A. Matter can be described by its physical properties. The physical properties of a substance generally depend on the spacing between the particles (atoms, molecules, ions) that make up the substance and the forces of attraction among them.
2.A.1: The different properties of solids and liquids can be explained by differences in their structures, both at the particulate level and in their supramolecular structures.
2.A.2: The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently.
2.A.3: Solutions are homogenous mixtures in which the physical properties are dependent on the concentration of the solute and the strengths of all interactions among the particles of the solutes and solvent.
B. Forces of attraction between particles (including the noble gases and also different parts of some large molecules) are important in determining many macroscopic properties of a substance, including how the observable physical state changes with temperature.

2.B.1: London dispersion forces are attractive forces present between all atoms and molecules. London dispersion forces are often the strongest net intermolecular force between large molecules.
2.B.2: Dipole forces result from the attraction among the positive ends and negative ends of polar molecules. Hydrogen bonding is a strong type of dipole-dipole force.
2.B.3: Intermolecular forces play a key role in determining the properties of substances, including biological structures and interactions.
C. The strong electrostatic forces of attraction holding atoms together in a unit are called chemical bonds.
2.C.1: In covalent bonding, electrons are shared between the nuclei of two atoms to form a molecule or polyatomic ion. Electronegativity differences between the two atoms account for the distribution of the shared electrons and the polarity of the bond.
2.C.2: Ionic bonding results from the net attraction between oppositely charged ions, closely packed together in a crystal lattice.
2.C.3: Metallic bonding describes an array of positively charged metal cores surrounded by a sea of mobile valence electrons.
2.C.4: The localized electron bonding model describes and predicts molecular geometry using Lewis diagrams and the VSEPR model.
D. The type of bonding in the solid state can be deduced from the properties of the solid state.
2.D.1: Ionic solids have high melting points, are brittle, and conduct electricity only when molten or in solution.
2.D.2: Metallic solids are good conductors of heat and electricity, have a wide range of melting points, and are shiny, malleable, ductile, and readily alloyed.
2.D.3: Covalent network solids generally have extremely high melting points, are hard, and are thermal insulators. Some conduct electricity.
2.D.4: Molecular solids with low molecular weight usually have low melting points and are not expected to conduct electricity as solids, in solution, or when molten.
3. Changes in matter involve the rearrangement and/or reorganization of atoms and/or the transfer of electrons.
A. Chemical changes are represented by a balanced chemical equation that identifies the ratios with which reactants react and products form.
3.A.1: A chemical change may be represented by a molecular, ionic, or net ionic equation.
3.A.2: Quantitative information can be derived from stoichiometric calculations that utilize the mole ratios from the balanced chemical equations. The role of stoichiometry in real-world applications is important to note, so that it does not seem to be simply an exercise done only by chemists.
B. Chemical reactions can be classified by considering what the reactants are, what the products are, or how they change from one into the other. Classes of chemical reactions include synthesis, decomposition, acid-base, and oxidation-reduction reactions.
3.B.1: Synthesis reactions are those in which atoms and/or molecules combine to form a new compound. Decomposition is the reverse of synthesis, a process whereby molecules are decomposed, often by the use of heat.
3.B.2: In a neutralization reaction, protons are transferred from an acid to a base.
3.B.3: In oxidation-reduction (redox) reactions, there is a net transfer of electrons. The species that loses electrons is oxidized, and the species that gains electrons is reduced.

C. Chemical and physical transformations may be observed in several ways and typically involve a change in energy.
3.C.1: Production of heat or light, formation of a gas, and formation of a precipitate and/or a color change are possible evidences that a chemical change has occurred.
3.C.2: Net changes in energy for a chemical reaction can be endothermic or exothermic.
3.C.3: Electrochemistry shows the interconversion between chemical and electrical energy in galvanic and electrolytic cells.
4. Rates of chemical reactions are determined by details of the molecular collisions.
A. Reaction rates that depend on temperature and other environmental factors are determined by measuring changes in concentrations of reactants or products over time.
4.A.1: The rate of a reaction is influenced by the concentration or pressure of reactants, the phase of the reactants and products, and environmental factors such as temperature and solvent.
4.A.2: The rate law shows how the rate depends on reactant concentrations.
4.A.3: The magnitude and temperature dependence of the rate of reaction is contained quantitatively in the rate constant.
B. Elementary reactions are mediated by collisions between molecules. Only collisions having sufficient energy and proper relative rientation of reactants lead to products.
4.B.1: Elementary reactions can be unimolecular or involve collisions between two or more molecules.
4.B.2: Not all collisions are successful. To get over the activation energy barrier, the colliding species need sufficient energy. Also, the orientations of the reactant molecules during the collision must allow for the rearrangement of reactant bonds to form product bonds.
4.B.3: A successful collision can be viewed as following a reaction path with an associated energy profile.
C. Many reactions proceed via a series of elementary reactions.
4.C.1: The mechanism of a multistep reaction consists of a series of elementary reactions that add up to the overall reaction.
4.C.2: In many reactions, the rate is set by the slowest elementary reaction, or rate-limiting step.
4.C.3: Reaction intermediates, which are formed during the reaction but not present in the overall reaction, play an important role in multistep reactions.
D. Reaction rates may be increased by the presence of a catalyst.
4.D.1: Catalysts function by lowering the activation energy of an elementary step in a reaction mechanism, and by providing a new and faster reaction mechanism.
4.D.2: Important classes in catalysis include acid-base catalysis, surface catalysis, and enzyme catalysis.
5. The laws of thermodynamics describe the essential role of energy and explain and predict the direction of changes in matter.
A. Two systems with different temperatures that are in thermal contact will exchange energy. The quantity of thermal energy transferred from one system to another is called heat.
5.A.1: Temperature is a measure of the average kinetic energy of atoms and molecules.
5.A.2: The process of kinetic energy transfer at the particulate scale is referred to in this course as heat transfer, and the spontaneous direction of the transfer is always from a hot to a cold body.
B. Energy is neither created nor destroyed, but only transformed from one form to another.
5.B.1: Energy is transferred between systems either through heat transfer or through one system doing work on the other system.

5.B.2: When two systems are in contact with each other and are otherwise isolated, the energy that comes out of one system is equal to the energy that goes into the other system. The combined energy of the two systems remains fixed. Energy transfer can occur through either heat exchange or work.
5.B.3: Chemical systems undergo three main processes that change their energy: heating/cooling, phase transitions, and chemical reactions.
5.B.4: Calorimetry is an experimental technique that is used to measure the change in energy of a chemical system.
C. Breaking bonds requires energy, and making bonds releases energy.
5.C.1: Potential energy is associated with a particular geometric arrangement of atoms or ions and the electrostatic interactions between them.
5.C.2: The net energy change during a reaction is the sum of the energy required to break the bonds in the reactant molecules and the energy released in forming the bonds of the product molecules. The net change in energy may be positive for endothermic reactions where energy is required, or negative for exothermic reactions where energy is released.
D. Electrostatic forces exist between molecules as well as between atoms or ions, and breaking the resultant intermolecular interactions requires energy.
5.D.1: Potential energy is associated with the interaction of molecules; as molecules draw near each other, they experience an attractive force.
5.D.2: At the particulate scale, chemical processes can be distinguished from physical processes because chemical bonds can be distinguished from intermolecular interactions.
5.D.3: Noncovalent and intermolecular interactions play important roles in many biological and polymer systems.
E. Chemical or physical processes are driven by a decrease in enthalpy or an increase in entropy, or both.
5.E.1: Entropy is a measure of the dispersal of matter and energy.
5.E.2: Some physical or chemical processes involve both a decrease in the internal energy of the components ($\Delta H^\circ < 0$) under consideration and an increase in the entropy of those components ($\Delta S^\circ > 0$). These processes are necessarily “thermodynamically favored” ($\Delta G^\circ < 0$).
5.E.3: If a chemical or physical process is not driven by both entropy and enthalpy changes, then the Gibbs free energy change can be used to determine whether the process is thermodynamically favored.
5.E.4: External sources of energy can be used to drive change in cases where the Gibbs free energy change is positive.
5.E.5: A thermodynamically favored process may not occur due to kinetic constraints (kinetic vs. thermodynamic control).
6. Any bond or intermolecular attraction that can be formed can be broken. These two processes are in a dynamic competition, sensitive to initial conditions and external perturbations.
A. Chemical equilibrium is a dynamic, reversible state in which rates of opposing processes are equal.
6.A.1: In many classes of reactions, it is important to consider both the forward and reverse reaction.
6.A.2: The current state of a system undergoing a reversible reaction can be characterized by the extent to which reactants have been converted to products. The relative quantities of reaction components are quantitatively described by the reaction quotient, Q.

6.A.3: When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$.
6.A.4: The magnitude of the equilibrium constant, K, can be used to determine whether the equilibrium lies toward the reactant side or product side.
B. Systems at equilibrium are responsive to external perturbations, with the response leading to a change in the composition of the system.
6.B.1: Systems at equilibrium respond to disturbances by partially countering the effect of the disturbance (LeChatelier's principle).
6.B.2: A disturbance to a system at equilibrium causes Q to differ from K, thereby taking the system out of the original equilibrium state. The system responds by bringing Q back into agreement with K, thereby establishing a new equilibrium state.
C. Chemical equilibrium plays an important role in acid-base chemistry and in solubility.
6.C.1: Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.
6.C.2: The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pK_a allows one to determine the protonation state of a molecule with a labile proton.
6.C.3: The solubility of a substance can be understood in terms of chemical equilibrium.
D. The equilibrium constant is related to temperature and the difference in Gibbs free energy between reactants and products.
6.D.1: When the difference in Gibbs free energy between reactants and products (ΔG°) is much larger than the thermal energy (RT), the equilibrium constant is either very small (for $\Delta G^\circ > 0$) or very large (for $\Delta G^\circ < 0$). When ΔG° is comparable to the thermal energy (RT), the equilibrium constant is near 1.

Potential Learning Objective Categories

Learning objective 1.1 The student can justify the observation that the ratio of the masses of the constituent elements in any pure sample of that compound is always identical on the basis of the atomic molecular theory. [*See* **SP 6.1; Essential knowledge 1.A.1**]
Learning objective 1.2 The student is able to select and apply mathematical routines to mass data to identify or infer the composition of pure substances and/or mixtures. [*See* **SP 2.2; Essential knowledge 1.A.2**]
Learning objective 1.3 The student is able to select and apply mathematical relationships to mass data in order to justify a claim regarding the identity and/or estimated purity of a substance. [*See* **SP 2.2, 6.1; Essential knowledge 1.A.2**]
Learning objective 1.4 The student is able to connect the number of particles, moles, mass, and volume of substances to one another, both qualitatively and quantitatively. [*See* **SP 7.1; Essential knowledge 1.A.3**]
Learning objective 1.5 The student is able to explain the distribution of electrons in an atom or ion based upon data. [*See* **SP 1.5, 6.2; Essential knowledge 1.B.1**]
Learning objective 1.6 The student is able to analyze data relating to electron energies for patterns and relationships. [*See* **SP 5.1; Essential knowledge 1.B.1**]

Learning objective 1.7 The student is able to describe the electronic structure of the atom, using PES data, ionization energy data, and/or Coulomb's Law to construct explanations of how the energies of electrons within shells in atoms vary. [*See* **SP 5.1, 6.2; Essential knowledge 1.B.2**]
Learning objective 1.8 The student is able to explain the distribution of electrons using Coulomb's Law to analyze measured energies. [*See* **SP 6.2; Essential knowledge 1.B.2**]
Learning objective 1.9 The student is able to predict and/or justify trends in atomic properties based on location on the periodic table and/or the shell model. [*See* **SP 6.4; Essential knowledge 1.C.1**]
Learning objective 1.10 Students can justify with evidence the arrangement of the periodic table and can apply periodic properties to chemical reactivity. [*See* **SP 6.1; Essential knowledge 1.C.1**]
Learning objective 1.11 The student can analyze data, based on periodicity and the properties of binary compounds, to identify patterns and generate hypotheses related to the molecular design of compounds for which data are not supplied. [*See* **SP 3.1, 5.1; Essential knowledge 1.C.1**]
Learning objective 1.12 The student is able to explain why a given set of data suggests, or does not suggest, the need to refine the atomic model from a classical shell model with the quantum mechanical model. [*See* **SP 6.3; Essential knowledge 1.C.2**]
Learning objective 1.13 Given information about a particular model of the atom, the student is able to determine if the model is consistent with specified evidence. [*See* **SP 5.3; Essential knowledge 1.D.1**]
Learning objective 1.14 The student is able to use data from mass spectrometry to identify the elements and the masses of individual atoms of a specific element. [*See* **SP 1.4, 1.5; Essential knowledge 1.D.2**]
Learning objective 1.15 The student can justify the selection of a particular type of spectroscopy to measure properties associated with vibrational or electronic motions of molecules. [*See* **SP 4.1; Essential knowledge 1.D.3**]
Learning objective 1.16 The student can design and/or interpret the results of an experiment regarding the absorption of light to determine the concentration of an absorbing species in a solution. [*See* **SP 4.2, 5.1; Essential knowledge 1.D.3**]
Learning objective 1.17 The student is able to express the law of conservation of mass quantitatively and qualitatively using symbolic representations and particulate drawings. [*See* **SP 1.5; Essential knowledge 1.E.1**]
Learning objective 1.18 The student is able to apply conservation of atoms to the rearrangement of atoms in various processes. [*See* **SP 1.4; Essential knowledge 1.E.2**]
Learning objective 1.19 The student can design, and/or interpret data from, an experiment that uses gravimetric analysis to determine the concentration of an analyte in a solution. [*See* **SP 4.2, 5.1; Essential knowledge 1.E.2**]
Learning objective 1.20 The student can design, and/or interpret data from, an experiment that uses titration to determine the concentration of an analyte in a solution. [*See* **SP 4.2, 5.1; Essential knowledge 1.E.2**]
Learning objective 2.1 Students can predict properties of substances based on their chemical formulas, and provide explanations of their properties based on particle views. [*See* **SP 6.4, 7.1; Essential knowledge components of 2.A-2.D**]
Learning objective 2.2 The student is able to explain the relative strengths of acids and bases based on molecular structure, interparticle forces, and solution equilibrium. [*See* **SP 7.2,** *connects to* **Big Idea 5, Big Idea 6; Essential knowledge components of 2.A-2.D**]
Learning objective 2.3 The student is able to use aspects of particulate models (i.e., particle spacing, motion, and forces of attraction) to reason about observed differences between solid and liquid phases and among solid and liquid materials. [*See* **SP 6.4, 7.1; Essential knowledge 2.A.1**]

Learning objective 2.4 The student is able to use KMT and concepts of intermolecular forces to make predictions about the macroscopic properties of gases, including both ideal and nonideal behaviors. [*See* **SP 1.4, 6.4; Essential knowledge 2.A.2**]

Learning objective 2.5 The student is able to refine multiple representations of a sample of matter in the gas phase to accurately represent the effect of changes in macroscopic properties on the sample. [*See* **SP 1.3, 6.4, 7.2; Essential knowledge 2.A.2**]

Learning objective 2.6 The student can apply mathematical relationships or estimation to determine macroscopic variables for ideal gases. [*See* **SP 2.2, 2.3; Essential knowledge 2.A.2**]

Learning objective 2.7 The student is able to explain how solutes can be separated by chromatography based on intermolecular interactions. [*See* **SP 6.2; Essential knowledge 2.A.3**]

Learning objective 2.8 The student can draw and/or interpret representations of solutions that show the interactions between the solute and solvent. [*See* **SP 1.1, 1.2, 6.4; Essential knowledge 2.A.3**]

Learning objective 2.9 The student is able to create or interpret representations that link the concept of molarity with particle views of solutions. [*See* **SP 1.1, 1.4; Essential knowledge 2.A.3**]

Learning objective 2.10 The student can design and/or interpret the results of a separation experiment (filtration, paper chromatography, column chromatography, or distillation) in terms of the relative strength of interactions among and between the components. [*See* **SP 4.2, 5.1; Essential knowledge 2.A.3**]

Learning objective 2.11 The student is able to explain the trends in properties and/or predict properties of samples consisting of particles with no permanent dipole on the basis of London dispersion forces. [*See* **SP 6.2, 6.4; Essential knowledge 2.B.1**]

Learning objective 2.12 The student can qualitatively analyze data regarding real gases to identify deviations from ideal behavior and relate these to molecular interactions. [*See* **SP 5.1, 6.5; Essential knowledge 2.B.2,** *connects to* **2.A.2**]

Learning objective 2.13 The student is able to describe the relationships between the structural features of polar molecules and the forces of attraction between the particles. [*See* **SP 1.4; Essential knowledge 2.B.2**]

Learning objective 2.14 The student is able to apply Coulomb's Law qualitatively (including using representations) to describe the interactions of ions, and the attractions between ions and solvents to explain the factors that contribute to the solubility of ionic compounds. [*See* **SP 1.4, 6.4; Essential knowledge 2.B.2**]

Learning objective 2.15 The student is able to explain observations regarding the solubility of ionic solids and molecules in water and other solvents on the basis of particle views that include intermolecular interactions and entropic effects. [*See* **SP 1.4, 6.2; Essential knowledge 2.B.3,** *connects to* **5.E.1**]

Learning objective 2.16 The student is able to explain the properties (phase, vapor pressure, viscosity, etc.) of small and large molecular compounds in terms of the strengths and types of intermolecular forces. [*See* **SP 6.2; Essential knowledge 2.B.3**]

Learning objective 2.17 The student can predict the type of bonding present between two atoms in a binary compound based on position in the periodic table and the electronegativity of the elements. [*See* **SP 6.4; Essential knowledge components of 2.C**]

Learning objective 2.18 The student is able to rank and justify the ranking of bond polarity on the basis of the locations of the bonded atoms in the periodic table. [*See* **SP 6.1; Essential knowledge 2.C.1**]

Learning objective 2.19 The student can create visual representations of ionic substances that connect the microscopic structure to macroscopic properties, and/or use representations to connect the microscopic structure to macroscopic properties (e.g., boiling point, solubility, hardness, brittleness, low volatility, lack of malleability, ductility, or conductivity). [*See* **SP 1.1, 1.4, 7.1; Essential knowledge 2.C.2,** *connects to* **2.D.1, 2.D.2**]

Learning objective 2.20 The student is able to explain how a bonding model involving delocalized electrons is consistent with macroscopic properties of metals (e.g., conductivity, malleability, ductility, and low volatility) and the shell model of the atom. [*See* **SP 6.2, 7.1; Essential knowledge 2.C.3,** *connects to* **2.D.2**]

Learning objective 2.21 The student is able to use Lewis diagrams and VSEPR to predict the geometry of molecules, identify hybridization, and make predictions about polarity. [*See* **SP 1.4; Essential knowledge 2.C.4**]

Learning objective 2.22 The student is able to design or evaluate a plan to collect and/or interpret data needed to deduce the type of bonding in a sample of a solid. [*See* **SP 4.2; Essential knowledge components of 2.D**]

Learning objective 2.23 The student can create a representation of an ionic solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.1**]

Learning objective 2.24 The student is able to explain a representation that connects properties of an ionic solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.1**]

Learning objective 2.25 The student is able to compare the properties of metal alloys with their constituent elements to determine if an alloy has formed, identify the type of alloy formed, and explain the differences in properties using particulate level reasoning. [*See* **SP 1.4, 7.2; Essential knowledge 2.D.2**]

Learning objective 2.26 Students can use the electron sea model of metallic bonding to predict or make claims about the macroscopic properties of metals or alloys. [*See* **SP 6.4, 7.1; Essential knowledge 2.D.2**]

Learning objective 2.27 The student can create a representation of a metallic solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.2**]

Learning objective 2.28 The student is able to explain a representation that connects properties of a metallic solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.2**]

Learning objective 2.29 The student can create a representation of a covalent solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.3**]

Learning objective 2.30 The student is able to explain a representation that connects properties of a covalent solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.3**]

Learning objective 2.31 The student can create a representation of a molecular solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.4**]

Learning objective 2.32 The student is able to explain a representation that connects properties of a molecular solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.4**]

Learning objective 3.1 Students can translate among macroscopic observations of change, chemical equations, and particle views. [*See* **SP 1.5, 7.1; Essential knowledge components of 3.A-3.C**]
Learning objective 3.2 The student can translate an observed chemical change into a balanced chemical equation and justify the choice of equation type (molecular, ionic, or net ionic) in terms of utility for the given circumstances. [*See* **SP 1.5, 7.1; Essential knowledge 3.A.1**]
Learning objective 3.3 The student is able to use stoichiometric calculations to predict the results of performing a reaction in the laboratory and/or to analyze deviations from the expected results. [*See* **SP 2.2, 5.1; Essential knowledge 3.A.2**]
Learning objective 3.4 The student is able to relate quantities (measured mass of substances, volumes of solutions, or volumes and pressures of gases) to identify stoichiometric relationships for a reaction, including situations involving limiting reactants and situations in which the reaction has not gone to completion. [*See* **SP 2.2, 5.1, 6.4; Essential knowledge 3.A.2**]
Learning objective 3.5 The student is able to design a plan in order to collect data on the synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions. [*See* **SP 2.1, 4.2; Essential knowledge 3.B.1**]
Learning objective 3.6 The student is able to use data from synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions. [*See* **SP 2.2, 6.1; Essential knowledge 3.B.1**]
Learning objective 3.7 The student is able to identify compounds as Brønsted-Lowry acids, bases, and/or conjugate acid-base pairs, using proton-transfer reactions to justify the identification. [*See* **SP 6.1; Essential knowledge 3.B.2**]
Learning objective 3.8 The student is able to identify redox reactions and justify the identification in terms of electron transfer. [*See* **SP 6.1; Essential knowledge 3.B.3**]
Learning objective 3.9 The student is able to design and/or interpret the results of an experiment involving a redox titration. [*See* **SP 4.2, 5.1; Essential knowledge 3.B.3**]
Learning objective 3.10 The student is able to evaluate the classification of a process as a physical change, chemical change, or ambiguous change based on both macroscopic observations and the distinction between rearrangement of covalent interactions and noncovalent interactions. [*See* **SP 1.4, 6.1; Essential knowledge 3.C.1,** *connects to* **5.D.2**]
Learning objective 3.11 The student is able to interpret observations regarding macroscopic energy changes associated with a reaction or process to generate a relevant symbolic and/or graphical representation of the energy changes. [*See* **SP 1.5, 4.4; Essential knowledge 3.C.2**]
Learning objective 3.12 The student can make qualitative or quantitative predictions about galvanic or electrolytic reactions based on half-cell reactions and potentials and/or Faraday's laws. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 3.C.3**]
Learning objective 3.13 The student can analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions. [*See* **SP 5.1; Essential knowledge 3.C.3**]
Learning objective 4.1 The student is able to design and/or interpret the results of an experiment regarding the factors (i.e., temperature, concentration, surface area) that may influence the rate of a reaction. [*See* **SP 4.2, 5.1; Essential knowledge 4.A.1**]
Learning objective 4.2 The student is able to analyze concentration vs. time data to determine the rate law for a zeroth-, first-, or second-order reaction. [*See* **SP 5.1; Essential knowledge 4.A.2,** *connects to* **4.A.3]**
Learning objective 4.3 The student is able to connect the half-life of a reaction to the rate constant of a first-order reaction and justify the use of this relation in terms of the reaction being a first-order reaction. [*See* **SP 2.1, 2.2; Essential knowledge 4.A.3**]

Learning objective 4.4 The student is able to connect the rate law for an elementary reaction to the frequency and success of molecular collisions, including connecting the frequency and success to the order and rate constant, respectively. [*See* **SP 7.1; Essential knowledge 4.B.1,** *connects to* **4.A.3, 4.B.2**]
Learning objective 4.5 The student is able to explain the difference between collisions that convert reactants to products and those that do not in terms of energy distributions and molecular orientation. [*See* **SP 6.2; Essential knowledge 4.B.2**]
Learning objective 4.6 The student is able to use representations of the energy profile for an elementary reaction (from the reactants, through the transition state, to the products) to make qualitative predictions regarding the relative temperature dependence of the reaction rate. [*See* **SP 1.4, 6.4; Essential knowledge 4.B.3**]
Learning objective 4.7 The student is able to evaluate alternative explanations, as expressed by reaction mechanisms, to determine which are consistent with data regarding the overall rate of a reaction, and data that can be used to infer the presence of a reaction intermediate. [*See* **SP 6.5;** *connects to* **Essential knowledge 4.C.1, 4.C.2, 4.C.3**]
Learning objective 4.8 The student can translate among reaction energy profile representations, particulate representations, and symbolic representations (chemical equations) of a chemical reaction occurring in the presence and absence of a catalyst. [*See* **SP 1.5; Essential knowledge 4.D.1**]
Learning objective 4.9 The student is able to explain changes in reaction rates arising from the use of acid-base catalysts, surface catalysts, or enzyme catalysts, including selecting appropriate mechanisms with or without the catalyst present. [*See* **SP 6.2, 7.2; Essential knowledge 4.D.2**]
Learning objective 5.1 The student is able to create or use graphical representations in order to connect the dependence of potential energy to the distance between atoms and factors, such as bond order (for covalent interactions) and polarity (for intermolecular interactions), which influence the interaction strength. [*See* **SP 1.1, 1.4, 7.2,** *connects to* **Big Idea 2; Essential knowledge components of 5.A-5.E**]
Learning objective 5.2 The student is able to relate temperature to the motions of particles, either via particulate representations, such as drawings of particles with arrows indicating velocities, and/or via representations of average kinetic energy and distribution of kinetic energies of the particles, such as plots of the Maxwell-Boltzmann distribution. [*See* **SP 1.1, 1.4, 7.1; Essential knowledge 5.A.1**]
Learning objective 5.3 The student can generate explanations or make predictions about the transfer of thermal energy between systems based on this transfer being due to a kinetic energy transfer between systems arising from molecular collisions. [*See* **SP 7.1; Essential knowledge 5.A.2**]
Learning objective 5.4 The student is able to use conservation of energy to relate the magnitudes of the energy changes occurring in two or more interacting systems, including identification of the systems, the type (heat versus work), or the direction of energy flow. [*See* **SP 1.4, 2.2,** *connects to* **Essential knowledge 5.B.1, 5.B.2**]
Learning objective 5.5 The student is able to use conservation of energy to relate the magnitudes of the energy changes when two nonreacting substances are mixed or brought into contact with one another. [*See* **SP 2.2,** *connects to* **Essential knowledge 5.B.1, 5.B.2**]
Learning objective 5.6 The student is able to use calculations or estimations to relate energy changes associated with heating/cooling a substance to the heat capacity, relate energy changes associated with a phase transition to the enthalpy of fusion/vaporization, relate energy changes associated with a chemical reaction to the enthalpy of the reaction, and relate energy changes to PΔV work. [*See* **SP 2.2, 2.3; Essential knowledge 5.B.3**]
Learning objective 5.7 The student is able to design and/or interpret the results of an experiment in which calorimetry is used to determine the change in enthalpy of a chemical process (heating/cooling, phase transition, or chemical reaction) at constant pressure. [*See* **SP 4.2, 5.1; Essential knowledge 5.B.4**]

Learning objective 5.8 The student is able to draw qualitative and quantitative connections between the reaction enthalpy and the energies involved in the breaking and formation of chemical bonds. [*See* **SP 2.3, 7.1, 7.2; Essential knowledge 5.C.2**]

Learning objective 5.9 The student is able to make claims and/or predictions regarding relative magnitudes of the forces acting within collections of interacting molecules based on the distribution of electrons within the molecules and the types of intermolecular forces through which the molecules interact. [*See* **SP 6.4; Essential knowledge 5.D.1**]

Learning objective 5.10 The student can support the claim about whether a process is a chemical or physical change (or may be classified as both) based on whether the process involves changes in intramolecular versus intermolecular interactions. [*See* **SP 5.1; Essential knowledge 5.D.2**]

Learning objective 5.11 The student is able to identify the noncovalent interactions within and between large molecules, and/or connect the shape and function of the large molecule to the presence and magnitude of these interactions. [*See* **SP 7.2; Essential knowledge 5.D.3**]

Learning objective 5.12 The student is able to use representations and models to predict the sign and relative magnitude of the entropy change associated with chemical or physical processes. [*See* **SP 1.4; Essential knowledge 5.E.1**]

Learning objective 5.13 The student is able to predict whether or not a physical or chemical process is thermodynamically favored by determination of (either quantitatively or qualitatively) the signs of both ΔH° and ΔS°, and calculation or estimation of ΔG° when needed. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 5.E.2,** *connects to* **5.E.3**]

Learning objective 5.14 The student is able to determine whether a chemical or physical process is thermodynamically favorable by calculating the change in standard Gibbs free energy. [*See* **SP 2.2; Essential knowledge 5.E.3,** *connects to* **5.E.2**]

Learning objective 5.15 The student is able to explain how the application of external energy sources or the coupling of favorable with unfavorable reactions can be used to cause processes that are not thermodynamically favorable to become favorable. [*See* **SP 6.2; Essential knowledge 5.E.4**]

Learning objective 5.16 The student can use LeChatelier's principle to make qualitative predictions for systems in which coupled reactions that share a common intermediate drive formation of a product. [*See* **SP 6.4; Essential knowledge 5.E.4,** *connects to* **6.B.1**]

Learning objective 5.17 The student can make quantitative predictions for systems involving coupled reactions that share a common intermediate, based on the equilibrium constant for the combined reaction. [*See* **SP 6.4; Essential knowledge 5.E.4,** *connects to* **6.A.2**]

Learning objective 5.18 The student can explain why a thermodynamically favored chemical reaction may not produce large amounts of product (based on consideration of both initial conditions and kinetic effects), or why a thermodynamically unfavored chemical reaction can produce large amounts of product for certain sets of initial conditions. [*See* **SP 1.3, 7.2; Essential knowledge 5.E.5,** *connects to* **6.D.1**]

Learning objective 6.1 The student is able to, given a set of experimental observations regarding physical, chemical, biological, or environmental processes that are reversible, construct an explanation that connects the observations to the reversibility of the underlying chemical reactions or processes. [*See* **SP 6.2; Essential knowledge 6.A.1**]

Learning objective 6.2 The student can, given a manipulation of a chemical reaction or set of reactions (e.g., reversal of reaction or addition of two reactions), determine the effects of that manipulation on Q or K. [*See* **SP 2.2; Essential knowledge 6.A.2**]

Learning objective 6.3 The student can connect kinetics to equilibrium by using reasoning about equilibrium, such as LeChatelier's principle, to infer the relative rates of the forward and reverse reactions. [*See* **SP 7.2; Essential knowledge 6.A.3**]

Learning objective 6.4 The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, *K*, use the tendency of *Q* to approach *K* to predict and justify the prediction as to whether the reaction will proceed toward products or reactants as equilibrium is approached. [*See* **SP 2.2, 6.4; Essential knowledge 6.A.3**]

Learning objective 6.5 The student can, given data (tabular, graphical, etc.) from which the state of a system at equilibrium can be obtained, calculate the equilibrium constant, *K*. [*See* **SP 2.2; Essential knowledge 6.A.3**]

Learning objective 6.6 The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, *K*, use stoichiometric relationships and the law of mass action (*Q* equals *K* at equilibrium) to determine qualitatively and/or quantitatively the conditions at equilibrium for a system involving a single reversible reaction. [*See* **SP 2.2, 6.4; Essential knowledge 6.A.3**]

Learning objective 6.7 The student is able, for a reversible reaction that has a large or small *K*, to determine which chemical species will have very large versus very small concentrations at equilibrium. [*See* **SP 2.2, 2.3; Essential knowledge 6.A.4**]

Learning objective 6.8 The student is able to use LeChatelier's principle to predict the direction of the shift resulting from various possible stresses on a system at chemical equilibrium. [*See* **SP 1.4, 6.4; Essential knowledge 6.B.1**]

Learning objective 6.9 The student is able to use LeChatelier's principle to design a set of conditions that will optimize a desired outcome, such as product yield. [*See* **SP 4.2; Essential knowledge 6.B.1**]

Learning objective 6.10 The student is able to connect LeChatelier's principle to the comparison of *Q* to *K* by explaining the effects of the stress on *Q* and *K*. [*See* **SP 1.4, 7.2; Essential knowledge 6.B.2**]

Learning objective 6.11 The student can generate or use a particulate representation of an acid (strong or weak or polyprotic) and a strong base to explain the species that will have large versus small concentrations at equilibrium. [*See* **SP 1.1, 1.4, 2.3; Essential knowledge 6.C.1**]

Learning objective 6.12 The student can reason about the distinction between strong and weak acid solutions with similar values of pH, including the percent ionization of the acids, the concentrations needed to achieve the same pH, and the amount of base needed to reach the equivalence point in a titration. [*See* **SP 1.4; Essential knowledge 6.C.1,** *connects to* **1.E.2**]

Learning objective 6.13 The student can interpret titration data for monoprotic or polyprotic acids involving titration of a weak or strong acid by a strong base (or a weak or strong base by a strong acid) to determine the concentration of the titrant and the p*K*a for a weak acid, or the p*K*b for a weak base. [*See* **SP 5.1; Essential knowledge 6.C.1,** *connects to* **I.E.2**]

Learning objective 6.14 The student can, based on the dependence of *K*w on temperature, reason that neutrality requires [H+] = [OH–] as opposed to requiring pH = 7, including especially the applications to biological systems. [*See* **SP 2.2, 6.2; Essential knowledge 6.C.1**]

Learning objective 6.15 The student can identify a given solution as containing a mixture of strong acids and/or bases and calculate or estimate the pH (and concentrations of all chemical species) in the resulting solution. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 6.C.1**]

Learning objective 6.16 The student can identify a given solution as being the solution of a monoprotic weak acid or base (including salts in which one ion is a weak acid or base), calculate the pH and concentration of all species in the solution, and/or infer the relative strengths of the weak acids or bases from given equilibrium concentrations. [*See* **SP 2.2, 6.4; Essential knowledge 6.C.1**]

Learning objective 6.17 The student can, given an arbitrary mixture of weak and strong acids and bases (including polyprotic systems), determine which species will react strongly with one another (i.e., with *K* >1) and what species will be present in large concentrations at equilibrium. [*See* **SP 6.4; Essential knowledge 6.C.1**]

Learning objective 6.18 The student can design a buffer solution with a target pH and buffer capacity by selecting an appropriate conjugate acid-base pair and estimating the concentrations needed to achieve the desired capacity. [*See* **SP 2.3, 4.2, 6.4; Essential knowledge 6.C.2**]
Learning objective 6.19 The student can relate the predominant form of a chemical species involving a labile proton (i.e., protonated/deprotonated form of a weak acid) to the pH of a solution and the p*K*a associated with the labile proton. [*See* **SP 2.3, 5.1, 6.4; Essential knowledge 6.C.2**]
Learning objective 6.20 The student can identify a solution as being a buffer solution and explain the buffer mechanism in terms of the reactions that would occur on addition of acid or base. [*See* **SP 6.4; Essential knowledge 6.C.2**]
Learning objective 6.21 The student can predict the solubility of a salt, or rank the solubility of salts, given the relevant K*sp* values. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 6.C.3**]
Learning objective 6.22 The student can interpret data regarding solubility of salts to determine, or rank, the relevant *Ksp* values. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 6.C.3**]
Learning objective 6.23 The student can interpret data regarding the relative solubility of salts in terms of factors (common ions, pH) that influence the solubility. [*See* **SP 5.1; Essential knowledge 6.C.3**]
Learning objective 6.24 The student can analyze the enthalpic and entropic changes associated with the dissolution of a salt, using particulate level interactions and representations. [*See* **SP 1.4, 7.1; Essential knowledge 6.C.3,** *connects to* **5.E**]
Learning objective 6.25 The student is able to express the equilibrium constant in terms of ΔG° and *RT* and use this relationship to estimate the magnitude of K and, consequently, the thermodynamic favorability of the process. [*See* **SP 2.3; Essential knowledge 6.D.1**]

Potential Science Practice Categories

Science Practice 1: The student can use representations and models to communicate scientific phenomena and solve scientific problems.
1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.
1.2 The student can *describe representations and models* of natural or man-made phenomena and systems in the domain.
1.3 The student can *refine representations and models* of natural or man-made phenomena and systems in the domain.
1.4 The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.
1.5 The student can *re-express key elements* of natural phenomena across multiple representations in the domain.
Science Practice 2: The student can use mathematics appropriately.
2.1 The student can *justify the selection of a mathematical routine* to solve problems.
2.2 The student can *apply mathematical routines* to quantities that describe natural phenomena.
2.3 The student can *estimate numerically* quantities that describe natural phenomena.
Science Practice 3: The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course.
3.1 The student can *pose scientific questions*.
3.2 The student can *refine scientific questions.*
3.3 The student can *evaluate scientific questions*.

Science Practice 4: The student can plan and implement data collection strategies in relation to a particular scientific question.
4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.
4.2 The student can *design a plan* for collecting data to answer a particular scientific question.
4.3 The student can *collect data* to answer a particular scientific question.
4.4 The student can *evaluate sources of data* to answer a particular scientific question.
Science Practice 5: The student can perform data analysis and evaluation of evidence.
5.1 The student can *analyze data* to identify patterns or relationships.
5.2 The student can *refine observations and measurements* based on data analysis.
5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.
Science Practice 6: The student can work with scientific explanations and theories.
6.1 The student can *justify claims with evidence*.
6.2 The student can *construct explanations of phenomena based on evidence* produced through scientific practices.
6.3 The student can *articulate the reasons that scientific explanations and theories are refined or replaced*.
6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.
6.5 The student can *evaluate alternative scientific explanations*.
Science Practice 7: The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains.
7.1 The student can *connect phenomena and models* across spatial and temporal scales.
7.2 The student can *connect concepts* in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.