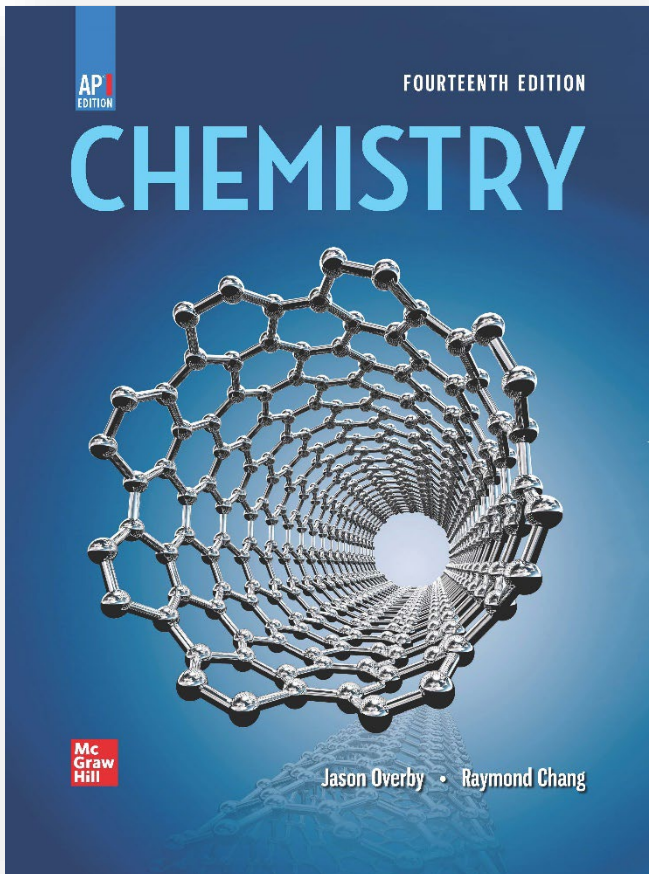
Advanced Placement®
CORRELATION GUIDE



Chemistry, AP Edition
©2023, 14e
Jason Overby & Raymond Chang

Based on the College Board Course Framework:
AP Chemistry, Effective Fall 2020

Table of Contents

Unit 1: Atomic Structure and Properties

Topic 1.1 Moles and Molar Mass		
Enduring Understanding SPQ-1 The mole allows different units to be compared.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SPQ-1.A Calculate quantities of a substance or its relative number of particles using dimensional analysis and the mole concept.	SPQ-1.A.1 One cannot count particles directly while performing laboratory work. Thus, there must be a connection between the masses of substances reacting and the actual number of particles undergoing chemical changes.	80-84, 100-106; 155-161; 196-199; 736-743
	SPQ-1.A.2 Avogadro's number ($N_A = 6.022 \times 10^{23}$ mol^{-1}) provides the connection between the number of moles in a pure sample of a substance and the number of constituent particles (or formula units) of that substance.	82-85, 100-106; 196-199
	SPQ-1.A.3 Expressing the mass of an individual atom or molecule in atomic mass units (amu) is useful because the average mass in amu of one particle (atom or molecule) or formula unit of a substance will always be numerically equal to the molar mass of that substance in grams. Thus, there is a quantitative connection between the mass of a substance and the number of particles that the substance contains. EQN: $n = m/M$	80-85

Topic 1.2 Mass Spectroscopy of Elements		
Enduring Understanding SPQ-1 The mole allows different units to be compared.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SPQ-1.B Explain the quantitative relationship between the mass spectrum of an element and the masses of the element's isotopes.	SPQ-1.B.1 The mass spectrum of a sample containing a single element can be used to determine the identity of the isotopes of that element and the relative abundance of each isotope in nature.	80-81, 88-89
	SPQ-1.B.2 The average atomic mass of an element can be estimated from the weighted average of the isotopic masses using the mass of each isotope and its relative abundance.	81, 88-89; AP123

Topic 1.3 Elemental Composition of Pure Substances		
Enduring Understanding **SPQ-2** Chemical formulas identify substances by their unique combination of atoms.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SPQ-2.A Explain the quantitative relationship between the elemental composition by mass and the empirical formula of a pure substance.	**SPQ-2.A.1** Some pure substances are composed of individual molecules, while others consist of atoms or ions held together in fixed proportions as described by a formula unit.	54-60; 494-500
	SPQ-2.A.2 According to the law of definite proportions, the ratio of the masses of the constituent elements in any pure sample of that compound is always the same.	42
	SPQ-2.A.3 The chemical formula that lists the lowest whole number ratio of atoms of the elements in a compound is the empirical formula.	57-58; 93-94

Topic 1.4 Composition of Mixtures		
Enduring Understanding **SPQ-2** Chemical formulas identify substances by their unique combination of atoms.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SPQ-2.B Explain the quantitative relationship between the elemental composition by mass and the composition of substances in a mixture.	**SPQ-2.B.1** While pure substances contain molecules or formula units of a single type, mixtures contain molecules or formula units of two or more types, whose relative proportions can vary	8-10; 150-154; 199-205; 936-937
	SPQ-2.B.2 Elemental analysis can be used to determine the relative numbers of atoms in a substance and to determine its purity	90-92; 155-157

Topic 1.5 Atomic Structure and Electron Configuration		
Enduring Understanding **SAP-1** Atoms and molecules can be identified by their electron distribution and energy.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-1.A Represent the electron configuration of an element or ions of an element using the Aufbau principle.	**SAP-1.A.1** The atom is composed of negatively charged electrons and a positively charged nucleus that is made of protons and neutrons.	43-49; 283-290
	SAP-1.A.2 Coulomb's law is used to calculate the force between two charged particles.	336-350, 375-380
	SAP-1.A.3 In atoms and ions, the electrons can be thought of as being in "shells (energy levels)" and "subshells (sublevels)," as described by the electron configuration. Inner electrons are called core electrons, and outer electrons are called valence electrons. The electron configuration is explained by quantum mechanics, as delineated in the Aufbau principle and exemplified in the periodic table of the elements.	290-317; 333-336; 371-372
	SAP-1.A.4 The relative energy required to remove an electron from different subshells of an atom or ion or from the same subshell in different atoms or ions (ionization energy) can be estimated through a qualitative application of Coulomb's law. This energy is related to the distance from the nucleus and the effective (shield) charge of the nucleus.	343-347

Topic 1.6 Photoelectron Spectroscopy		
Enduring Understanding **SAP-1** Atoms and molecules can be identified by their electron distribution and energy.		
Learning Objective	**Essential Knowledge**	**Page number**
SAP-1.B Explain the relationship between the photoelectron spectrum of an atom or ion and: a. The electron configuration of the species. b. The interactions between the electrons and the nucleus.	**SAP-1.B.1** The energies of the electrons in a given shell can be measured experimentally with photoelectron spectroscopy (PES). The position of each peak in the PES spectrum is related to the energy required to remove an electron from the corresponding subshell, and the height of each peak is (ideally) proportional to the number of electrons in that subshell.	281-283 **see additional online activity*

Topic 1.7 Periodic Trends		
Enduring Understanding **SAP-2** The periodic table shows patterns in electronic structure and trends in atomic properties.		
Learning Objective **SAP-2.A** Explain the relationship between trends in atomic properties of elements and electronic structure and periodicity.	**Essential Knowledge** **SAP-2.A.1** The organization of the periodic table is based on the recurring properties of the elements and explained by the pattern of electron configurations and the presence of completely or partially filled shells (and subshells) of electrons in atoms.	**Page number** 51-52; 329-336
	SAP-2.A.2 Trends in atomic properties within the periodic table (periodicity) can be qualitatively understood through the position of the element in the periodic table, Coulomb's law, the shell model, and the concept of shielding/effective nuclear charge. These properties include: a. Ionization energy b. Atomic and ionic radii c. Electron affinity d. Electronegativity.	336-350
	SAP-2.A.3 The periodicity (in SAP-2.A.2) is useful to predict/estimate values of properties in the absence of data.	336-350

Topic 1.8 Valence Electrons and Ionic Compounds		
Enduring Understanding **SAP-2** The periodic table shows patterns in electronic structure and trends in atomic properties.		
Learning Objective **SAP-2.B** Explain the relationship between trends in the reactivity of elements and periodicity.	**Essential Knowledge** **SAP-2.B.1** The likelihood that two elements will form a chemical bond is determined by the interactions between the valence electrons and nuclei of elements.	**Page numbers** 54-60; 333, 350-361
	SAP-2.B.2 Elements in the same column of the periodic table tend to form analogous compounds.	51-52; 947-952; 989-994
	SAP-2.B.3 Typical charges of atoms in ionic compounds are governed by their location on the periodic table and the number of valence electrons.	54-55; 334-336; 372-374; 947-952; 989-994

Back to Table of Contents

Unit 2: Molecular and Ionic Compound Structure and Properties

Topic 2.1 Types of Chemical Bonds		
Enduring Understanding **SAP-3** Atoms or ions bond due to interactions between them, forming molecules.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-3.A Explain the relationship between the type of bonding and the properties of the elements participating in the bond.	**SAP-3.A.1** Electronegativity values for the representative elements increase going from left to right across a period and decrease going down a group. These trends can be understood qualitatively through the electronic structure of the atoms, the shell model, and Coulomb's law.	383-385
	SAP-3.A.2 Valence electrons shared between atoms of similar electronegativity constitute a nonpolar covalent bond. For example, bonds between carbon and hydrogen are effectively nonpolar even though carbon is slightly more electronegative than hydrogen.	54-55; 380-382, 385-386; 429-434
	SAP-3.A.3 Valence electrons shared between atoms of unequal electronegativity constitute a polar covalent bond. a. The atom with a higher electronegativity will develop a partial negative charge relative to the other atom in the bond. b. In single bonds, greater differences in electronegativity lead to greater bond dipoles. c. All polar bonds have some ionic character, and the difference between ionic and covalent bonding is not distinct but rather a continuum.	54-55; 383-387; 429-434
	SAP-3.A.4 The difference in electronegativity is not the only factor in determining if a bond should be designated as ionic or covalent. Generally, bonds between a metal and nonmetal are ionic, and bonds between two nonmetals are covalent. Examination of the properties of a compound is the best way to characterize the type of bonding.	343-347; 383-387
	SAP-3.A.5 In a metallic solid, the valence electrons from the metal atoms are considered to be delocalized and not associated with any individual atom.	497-499; 943-944

Topic 2.2 Intramolecular Force and Potential Energy		
Enduring Understanding **SAP-3** Atoms or ions bond due to interactions between them, forming molecules.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-3.B Represent the relationship between potential energy and distance between atoms, based on factors that influence the interaction strength.	**SAP-3.B.1** A graph of potential energy versus the distance between atoms is a useful representation for describing the interactions between atoms. Such graphs illustrate both the equilibrium bond length (the separation between atoms at which the potential energy is lowest) and the bond energy (the energy required to separate the atoms).	383; 434-436
	SAP-3.B.2 In a covalent bond, the bond length is influenced by both the size of the atom's core and the bond order (i.e., single, double, triple). Bonds with a higher order are shorter and have larger bond energies.	382-383, 403-408
	SAP-3.B.3 Coulomb's law can be used to understand the strength of interactions between cations and anions. a. Because the interaction strength is proportional to the charge on each ion, larger charges lead to stronger interactions. b. Because the interaction strength increases as the distance between the centers of the ions (nuclei) decreases, smaller ions lead to stronger interactions.	259-261; 339-340; 375-382

Topic 2.3 Structure of Ionic Solids		
Enduring Understanding **SAP-3** Atoms or ions bond due to interactions between them, forming molecules.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-3.C Represent an ionic solid with a particulate model that is consistent with Coulomb's law and the properties of the constituent ions.	**SAP-3.C.1** The cations and anions in an ionic crystal are arranged in a systematic, periodic 3-D array that maximizes the attractive forces among cations and anions while minimizing the repulsive forces.	494-496

Topic 2.4 Structure of Metals and Alloys

Enduring Understanding
SAP-3 Atoms or ions bond due to interactions between them, forming molecules.

Learning Objective	Essential Knowledge	Page numbers
SAP-3.D Represent a metallic solid and/or alloy using a model to show essential characteristics of the structure and interactions present in the substance.	**SAP-3.D.1** Metallic bonding can be represented as an array of positive metal ions surrounded by delocalized valence electrons (i.e., a "sea of electrons").	497-498; 943-944
	SAP-3.D.2 Interstitial alloys form between atoms of different radii, where the smaller atoms fill the interstitial spaces between the larger atoms (e.g., with steel in which carbon occupies the interstices in iron).	938-941
	SAP-3.D.3 Substitutional alloys form between atoms of comparable radius, where one atom substitutes for the other in the lattice. (In certain brass alloys, other elements, usually zinc, substitute for copper.)	936

Topic 2.5 Lewis Diagrams

Enduring Understanding
SAP-4 Molecular compounds are arranged based on Lewis diagrams and Valence Shell Electron Pair Repulsion (VSEPR) theory.

Learning Objective	Essential Knowledge	Page numbers
SAP-4.A Represent a molecule with a Lewis diagram.	**SAP-4.A.1** Lewis diagrams can be constructed according to an established set of principles.	388-394

Topic 2.6 Resonance and Formal Charge

Enduring Understanding
SAP-4 Molecular compounds are arranged based on Lewis diagrams and Valence Shell Electron Pair Repulsion (VSEPR) theory.

Learning Objective	Essential Knowledge	Page numbers
SAP-4.B Represent a molecule with a Lewis diagram that accounts for resonance between equivalent structures or that uses formal charge to select between nonequivalent structures.	**SAP-4.B.1** In cases where more than one equivalent Lewis structure can be constructed, resonance must be included as a refinement to the Lewis structure. In many such cases, this refinement is needed to provide qualitatively accurate predictions of molecular structure and properties.	393-394
	SAP-4.B.2 The octet rule and formal charge can be used as criteria for determining which of several possible valid Lewis diagrams provides the best model for predicting molecular structure and properties.	391-394
	SAP-4.B.3 As with any model, there are limitations to the use of the Lewis structure model, particularly in cases with an odd number of valence electrons.	397-398

Topic 2.7 VSEPR and Bond Hybridization

Enduring Understanding

SAP-4 Molecular compounds are arranged based on Lewis diagrams and Valence Shell Electron Pair Repulsion (VSEPR) theory.

Learning Objective	Essential Knowledge	Page numbers
SAP-4.C Based on the relationship between Lewis diagrams, VSEPR theory, bond orders, and bond polarities: a. Explain structural properties of molecules. b. Explain electron properties of molecules.	**SAP-4.C.1** VSEPR theory uses the Coulombic repulsion between electrons as a basis for predicting the arrangement of electron pairs around a central atom.	419
	SAP-4.C.2 Both Lewis diagrams and VSEPR theory must be used for predicting electronic and structural properties of many covalently bonded molecules and polyatomic ions, including the following: a. Molecular geometry b. Bond angles c. Relative bond energies based on bond order d. Relative bond lengths (multiple bonds, effects of atomic radius) e. Presence of a dipole moment f. Hybridization of valence orbitals of the molecule	419-428
	SAP-4.C.3 The terms “hybridization” and “hybrid atomic orbital” are used to describe the arrangement of electrons around a central atom. When the central atom is *sp* hybridized, its ideal bond angles are 180°; for sp^2 hybridized atoms the bond angles are 120°; and for sp^3 hybridized atoms the bond angles are 109.5°.	437-445
	SAP-4.C.4 Bond formation is associated with overlap between atomic orbitals. In multiple bonds, such overlap leads to the formation of both sigma and pi bonds. The overlap is stronger in sigma than pi bonds, which is reflected in sigma bonds having greater bond energy than pi bonds. The presence of a pi bond also prevents the rotation of the bond and leads to structural isomers.	449-457

Back to Table of Contents

Unit 3: Intermolecular Forces and Properties

Topic 3.1 Intermolecular Forces		
Enduring Understanding **SAP-5** Intermolecular forces can explain the physical properties of a material.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-5.A Explain the relationship between the chemical structures of molecules and the relative strength of their intermolecular forces when: a. The molecules are of the same chemical species. b. The molecules are of two different chemical species.	**SAP-5.A.1** London dispersion forces are a result of the Coulombic interactions between temporary, fluctuating dipoles. London dispersion forces are often the strongest net intermolecular force between large molecules. a. Dispersion forces increase with increasing contact area between molecules and with increasing polarizability of the molecules. b. The polarizability of a molecule increases with an increasing number of electrons in the molecule; and the size of the electron cloud. It is enhanced by the presence of pi bonding. c. The term "London dispersion forces" should not be used synonymously with the term "van der Waals forces."	473-476; 1064-1069
	SAP-5.A.2 The dipole moment of a polar molecule leads to additional interactions with other chemical species. a. Dipole-induced dipole interactions are present between a polar and nonpolar molecule. These forces are always attractive. The strength of these forces increases with the magnitude of the dipole of the polar molecule and with the polarizability of the nonpolar molecule. b. Dipole-dipole interactions are present between polar molecules. The interaction strength depends on the magnitudes of the dipoles and their relative orientation. Interactions between polar molecules are typically greater than those between nonpolar molecules of comparable size because these interactions act in addition to London dispersion forces. c. Ion-dipole forces of attraction are present between ions and polar molecules. These tend to be stronger than dipole-dipole forces.	429-430; 473-476; 530; 1042

Topic 3.1 Intermolecular Forces (continued)		
Enduring Understanding **SAP-5** Intermolecular forces can explain the physical properties of a material.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-5.A Explain the relationship between the chemical structures of molecules and the relative strength of their intermolecular forces when: a. The molecules are of the same chemical species. b. The molecules are of two different chemical species.	**SAP-5.A.3** The relative strength and orientation dependence of dipole-dipole and ion-dipole forces can be understood qualitatively by considering the sign of the partial charges responsible for the molecular dipole moment, and how these partial charges interact with an ion or with an adjacent dipole.	473-476
	SAP-5.A.4 Hydrogen bonding is a strong type of intermolecular interaction that exists when hydrogen atoms covalently bonded to the highly electronegative atoms (N, O, and F) are attracted to the negative end of a dipole formed by the electronegative atom (N, O, and F) in a different molecule, or a different part of the same molecule.	473-476
	SAP-5.A.5 In large biomolecules, noncovalent interactions may occur between different molecules or between different regions of the same large biomolecule.	1072-1080

Topic 3.2 Properties of Solids		
Enduring Understanding **SAP-5** Intermolecular forces can explain the physical properties of a material.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-5.B Explain the relationship among the macroscopic properties of a substance, the particulate-level structure of the substance, and the interactions between these particles.	**SAP-5.B.1** Many properties of liquids and solids are determined by the strengths and types of intermolecular forces present. Because intermolecular interactions are broken when a substance vaporizes, the vapor pressure and boiling point are directly related to the strength of those interactions. Melting points also tend to correlate with interaction strength, but because the interactions are only rearranged, in melting, the relations can be more subtle.	502-509
	SAP-5.A.2 Particulate-level representations, showing multiple interacting chemical species, are a useful means to communicate or understand how intermolecular interactions help to establish macroscopic properties.	126-128; 472-473, 477-478, 483; 529; 683; 1073-1074, 1080

Topic 3.2 Properties of Solids (continued)		
Enduring Understanding **SAP-5** Intermolecular forces can explain the physical properties of a material.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-5.B Explain the relationship among the macroscopic properties of a substance, the particulate-level structure of the substance, and the interactions between these particles.	**SAP-5.B.3** Due to strong interactions between ions, ionic solids tend to have low vapor pressures, high melting points, and high boiling points. They tend to be brittle due to the repulsion of like charges caused when one layer slides across another layer. They conduct electricity only when the ions are mobile, as when the ionic solid is melted or dissolved in water or another solvent.	125-127; 176-177; 375-380, 382; 494-499
	SAP-5.B.4 In covalent network solids, the atoms are covalently bonded together into a three-dimensional network (e.g., diamond) or layers of two-dimensional networks (e.g., graphite). These are only formed from nonmetals: elemental (e.g., diamond, graphite) or binary compounds of two nonmetals (e.g., silicon dioxide and silicon carbide). Due to the strong covalent interactions, covalent solids have high melting points. Three-dimensional network solids are also rigid and hard, because the covalent bond angles are fixed. However, graphite is soft because adjacent layers can slide past each other relatively easily	496-497
	SAP-5.B.5 Molecular solids are composed of distinct, individual units of covalently-bonded molecules attracted to each other through relatively weak intermolecular forces. Molecular solids generally have a low melting point because of the relatively weak intermolecular forces present between the molecules. They do not conduct electricity because their valence electrons are tightly held within the covalent bonds and the lone pairs of each constituent molecule. Molecular solids are sometimes composed of very large molecules or polymers.	176-177; 380-383; 496-497; 1063-1068

Topic 3.2 Properties of Solids (continued)		
Enduring Understanding **SAP-5** Intermolecular forces can explain the physical properties of a material.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-5.B Explain the relationship among the macroscopic properties of a substance, the particulate-level structure of the substance, and the interactions between these particles.	**SAP-5.B.6** Metallic solids are good conductors of electricity and heat, due to the presence of free valence electrons. They also tend to be malleable and ductile, due to the ease with which the metal cores can rearrange their structure. In an interstitial alloy, interstitial atoms tend to make the lattice more rigid, decreasing malleability and ductility. Alloys typically retain a sea of mobile electrons and so remain conducting.	497-498; 936, 938-944
	SAP-5.B.7 In large biomolecules or polymers, noncovalent interactions may occur between different molecules or between different regions of the same large biomolecule. The functionality and properties of such molecules depend strongly on the shape of the molecule, which is largely dictated by noncovalent interactions.	1054-1055; 1072-1075, 1078-1080

Topic 3.3 Solids, Liquids, and Gases		
Enduring Understanding **SAP-6** Matter exists in three states: solid, liquid, and gas, and their differences are influenced by variances in spacing and motion of the molecules.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-6.A Represent the differences between solid, liquid, and gas phases using a particulate-level model.	**SAP-6.A.1** Solids can be crystalline, where the particles are arranged in a regular three-dimensional structure, or they can be amorphous, where the particles do not have a regular, orderly arrangement. In both cases, the motion of the individual particles is limited, and the particles do not undergo overall translation with respect to each other. The structure of the solid is influenced by interparticle interactions and the ability of the particles to pack together.	11-13; 485-491, 494-498
	SAP-6.A.2 The constituent particles in liquids are in close contact with each other, and they are continually moving and colliding. The arrangement and movement of particles are influenced by the nature and strength of the forces (e.g., polarity, hydrogen bonding, and temperature) between the particles.	11-13; 479-484

Topic 3.3 Solids, Liquids, and Gases (continued)

Enduring Understanding

SAP-6 Matter exists in three states: solid, liquid, and gas, and their differences are influenced by variances in spacing and motion of the molecules.

Learning Objective	Essential Knowledge	Page numbers
SAP-6.A Represent the differences between solid, liquid, and gas phases using a particulate-level model.	**SAP-6.A.3** The solid and liquid phases for a particular substance typically have similar molar volume because, in both phases, the constituent particles are in close contact at all times.	11-13; 508-511
	SAP-6.A.4 In the gas phase, the particles are in constant motion. Their frequencies of collision and the average spacing between them are dependent on temperature, pressure, and volume. Because of this constant motion, and minimal effects of forces between particles, a gas has neither a definite volume nor a definite shape.	11-13; 178, 206-207

Topic 3.4 Ideal Gas Law

Enduring Understanding

SAP-7 Gas properties are explained macroscopically—using the relationships among pressure, volume, temperature, moles, gas constant—and molecularly by the motion of the gas.

Learning Objective	Essential Knowledge	Page numbers
SAP-7.A Explain the relationship between the macroscopic properties of a sample of gas or mixture of gases using the ideal gas law.	**SAP-7.A.1** The macroscopic properties of ideal gases are related through the ideal gas law: EQN: $PV = nRT$.	188-199, 214-216; 634-635, 654-655
	SAP-7.A.2 In a sample containing a mixture of ideal gases, the pressure exerted by each component (the partial pressure) is independent of the other components. Therefore, the total pressure of the sample is the sum of the partial pressures. EQN: $P_A = P_{total} \times X_A$[3] where XA = moles A/total moles; EQN: $P_{total} = P_A + P_B + P_C + \ldots$	199-205; 654-655
	SAP-7.A.3 Graphical representations of the relationships between *P*, *V*, *T*, and *n* are useful to describe gas behavior.	184, 185, 204, 208, 214; 797

<table>
<tr><td colspan="3">Topic 3.5 Kinetic Molecular Theory</td></tr>
<tr><td colspan="3">Enduring Understanding
SAP-7 Gas properties are explained macroscopically—using the relationships among pressure, volume, temperature, moles, gas constant—and molecularly by the motion of the gas.</td></tr>
<tr><td rowspan="4">Learning Objective
SAP-7.B Explain the relationship between the motion of particles and the macroscopic properties of gases with:
a. The kinetic molecular theory (KMT).
b. A particulate model.
c. A graphical representation.</td><td>Essential Knowledge
SAP-7.B.1 The kinetic molecular theory (KMT) relates the macroscopic properties of gases to motions of the particles in the gas. The Maxwell-Boltzmann distribution describes the distribution of the kinetic energies of particles at a given temperature.</td><td>Page numbers
205-216; 593-596</td></tr>
<tr><td>SAP-7.B.2 All the particles in a sample of matter are in continuous, random motion. The average kinetic energy of a particle is related to its average velocity by the equation:
EQN: $KE = \frac{1}{2} mv^2$</td><td>205-206</td></tr>
<tr><td>SAP-7.B.3 The Kelvin temperature of a sample of matter is proportional to the average kinetic energy of the particles in the sample.</td><td>184-186; 593-596</td></tr>
<tr><td>SAP-7.B.4 The Maxwell-Boltzmann distribution provides a graphical representation of the energies/ velocities of particles at a given temperature.</td><td>207-209</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 3.6 Deviation from Ideal Gas Law</td></tr>
<tr><td colspan="3">Enduring Understanding
SAP-7 Gas properties are explained macroscopically—using the relationships among pressure, volume, temperature, moles, gas constant—and molecularly by the motion of the gas.</td></tr>
<tr><td>Learning Objective
SAP-7.C Explain the relationship among non-ideal behaviors of gases, interparticle forces, and/or volumes.</td><td>Essential Knowledge
SAP-7.C.1 The ideal gas law does not explain the actual behavior of real gases. Deviations from the ideal gas law may result from interparticle attractions among gas molecules, particularly at conditions that are close to those resulting in condensation. Deviations may also arise from particle volumes, particularly at extremely high pressures.</td><td>Page numbers
188-189; 214-216</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 3.7 Solutions and Mixtures</td></tr>
<tr><td colspan="3">Enduring Understanding
SPQ-3 Interactions between intermolecular forces influence the solubility and separation of mixtures.</td></tr>
<tr><td rowspan="2">Learning Objective
SPQ-3.A Calculate the number of solute particles, volume, or molarity of solutions.</td><td>Essential Knowledge
SPQ-3.A.1 Solutions, also sometimes called homogeneous mixtures, can be solids, liquids, or gases. In a solution, the macroscopic properties do not vary throughout the sample. In a heterogeneous mixture, the macroscopic properties depend on location in the mixture.</td><td>Page numbers
8-9; 125; 199-201, 202-203; 528-531, 554-557; 753-758</td></tr>
<tr><td>Essential Knowledge
SPQ-3.A.2 Solution composition can be expressed in a variety of ways; molarity is the most common method used in the laboratory.
EQN: $M = n_{solute} / L_{solution}$</td><td>150-154, 157-162; 532-536</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 3.8 Representations of Solutions</td></tr>
<tr><td colspan="3">Enduring Understanding
SPQ-3 Interactions between intermolecular forces influence the solubility and separation of mixtures.</td></tr>
<tr><td>Learning Objective
SPQ-3.B Using particulate models for mixtures:
a. Represent interactions between components.
b. Represent concentrations of components.</td><td>Essential Knowledge
SPQ-3.B.1 Particulate representations of solutions communicate the structure and properties of solutions, by illustration of the relative concentrations of the components in the solution and drawings that show interactions among the components.</td><td>Page numbers
126-128, 139-140, 153; 199; 529, 539, 553, 556-557; 683, 701</td></tr>
</table>

Topic 3.9 Separation of Solutions and Mixtures Chromatography		
Enduring Understanding **SPQ-3** Interactions between intermolecular forces influence the solubility and separation of mixtures.		
Learning Objective **SPQ-3.C** Explain the relationship between the solubility of ionic and molecular compounds in aqueous and nonaqueous solvents, and the intermolecular interactions between particles.	**Essential Knowledge** **SPQ-3.C.1** The components of a liquid solution cannot be separated by filtration. They can, however, be separated using processes that take advantage of differences in the intermolecular interactions of the components. a. Chromatography (paper, thin-layer, and column) separates chemical species by taking advantage of the differential strength of intermolecular interactions between and among the components of the solution (the mobile phase) and with the surface components of the stationary phase. b. Distillation separates chemical species by taking advantage of the differential strength of intermolecular interactions between and among the components and the effects these interactions have on the vapor pressures of the components in the mixture.	**Page numbers** 359; 429-433 **See additional online activity;* 544; 1054-1056

Topic 3.10 Solubility		
Enduring Understanding **SPQ-3** Interactions between intermolecular forces influence the solubility and separation of mixtures.		
Learning Objective **SPQ-3.C** Explain the relationship between the solubility of ionic and molecular compounds in aqueous and nonaqueous solvents, and the intermolecular interactions between particles.	**Essential Knowledge** **SPQ-3.C.2** Substances with similar intermolecular interactions tend to be miscible or soluble in one another	**Page numbers** 128; 528-531,, 537-541; 747-748, 755, 759-764

<table>
<tr><th colspan="3">Topic 3.11 Spectroscopy and the Electromagnetic Spectrum</th></tr>
<tr><td colspan="3">Enduring Understanding
SAP-8 Spectroscopy can determine the structure and concentration in a mixture of a chemical species.</td></tr>
<tr><td>Learning Objective
SAP-8.A Explain the relationship between a region of the electromagnetic spectrum and the types of molecular or electronic transitions associated with that region.</td><td>Essential Knowledge
SAP-8.A.1 Differences in absorption or emission of photons in different spectral regions are related to the different types of molecular motion or electronic transition:
a. Microwave radiation is associated with transitions in molecular rotational levels.
b. Infrared radiation is associated with transitions in molecular vibrational levels.
c. Ultraviolet/visible radiation is associated with transitions in electronic energy levels.</td><td>Page numbers
275-290; 917-918</td></tr>
</table>

<table>
<tr><th colspan="3">Topic 3.12 Photoelectric Effect</th></tr>
<tr><td colspan="3">Enduring Understanding
SAP-8 Spectroscopy can determine the structure and concentration in a mixture of a chemical species.</td></tr>
<tr><td rowspan="2">Learning Objective
SAP-8.B Explain the properties of an absorbed or emitted photon in relationship to an electronic transition in an atom or molecule.</td><td>Essential Knowledge
SAP-8.B.1 When a photon is absorbed (or emitted) by an atom or molecule, the energy of the species is increased (or decreased) by an amount equal to the energy of the photon.</td><td>Page numbers
274, 275-290; 1015-1016</td></tr>
<tr><td>SAP-8.B.2 The wavelength of the electromagnetic wave is related to its frequency and the speed of light by the equation:
EQN: $c = \lambda \nu$.
The energy of a photon is related to the frequency of the electromagnetic wave through Planck’s equation ($E = h\nu$).</td><td>274, 278-280; 1015-1017</td></tr>
</table>

Topic 3.13 Beer-Lambert Law		
Enduring Understanding **SAP-8** Spectroscopy can determine the structure and concentration in a mixture of a chemical species.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-8.C Explain the amount of light absorbed by a solution of molecules or ions in relationship to the concentration, path length, and molar absorptivity.	**SAP-8.C.1** The Beer-Lambert law relates the absorption of light by a solution to three variables according to the equation: EQN: $A = \varepsilon bc$. The molar absorptivity ε describes how intensely a sample of molecules or ions absorbs light of a specific wavelength. The path length b and concentration c are proportional to the number of absorbing species.	149; 570; 1015-1017
	SAP-8.C.2 In most experiments the path length and wavelength of light are held constant. In such cases, the absorbance is proportional only to the concentration of absorbing molecules or ions.	532-536; 1015-1017

Back to Table of Contents

Unit 4: Chemical Reactions

Topic 4.1 Introduction for Reactions		
Enduring Understanding **TRA-1** A substance that changes its properties, or that changes into a different substance, can be represented by chemical equations.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-1.A Identify evidence of chemical and physical changes in matter	**TRA-1.A.1** A physical change occurs when a substance undergoes a change in properties but not a change in composition. Changes in the phase of a substance (solid, liquid, gas) or formation/ separation of mixtures of substances are common physical changes.	13-14; 472, 502-516
	TRA-1.A.2 A chemical change occurs when substances are transformed into new substances, typically with different compositions. Production of heat or light, formation of a gas, formation of a precipitate, and/or color change provide possible evidence that a chemical change has occurred.	13-14; 95; 127, 132, 136-138 139, 144-148, 155-157; 232-234

Topic 4.2 Net Ionic Equations		
Enduring Understanding **TRA-1** A substance that changes its properties, or that changes into a different substance, can be represented by chemical equations.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-1.B Represent changes in matter with a balanced chemical or net ionic equation: a. For physical changes. b. For given information about the identity of the reactants and/or product. c. For ions in a given chemical reaction.	**TRA-1.B.1** All physical and chemical processes can be represented symbolically by balanced equations.	95-100; 129-132; 816-818
	TRA-1.B.2 Chemical equations represent chemical changes. These changes are the result of a rearrangement of atoms into new combinations; thus, any representation of a chemical change must contain equal numbers of atoms of every element before and after the change occurred. Equations thus demonstrate that mass is conserved in chemical reactions.	95-100; 129-132; 372-373, 380-381; 816-818
	TRA-1.B.3 Balanced molecular, complete ionic, and net ionic equations are differing symbolic forms used to represent a chemical reaction. The form used to represent the reaction depends on the context in which it is to be used.	95-100; 129-132; 816-818

Topic 4.3 Representations of Reactions		
Enduring Understanding **TRA-1** A substance that changes its properties, or that changes into a different substance, can be represented by chemical equations.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-1.C Represent a given chemical reaction or physical process with a consistent particulate model.	**TRA-1.C.1** Balanced chemical equations in their various forms can be translated into symbolic particulate representations.	3, 14; 41, 42; 96, 100, 107, 116, 117, 118, 120; 126, 135; 187; 243, 246, 261, 267; 378, 398, 402, 406, 407, 414; 529; 569, 572, 576, 578, 582, 584, 586, 588, 595, 596, 597, 601, 603, 604, 609, 613, 618, 619, 620, 621, 622, 623; 631, 637, 638, 639, 646, 647, 651; 654, 658, 660, 662, 667, 668; 675, 683; 769, 770; 783, 789, 791, 808, 811, 813; 820; 877; 1072, 1077

Topic 4.4 Physical and Chemical Changes		
Enduring Understanding **TRA-1** A substance that changes its properties, or that changes into a different substance, can be represented by chemical equations.		
Learning Objective	**Essential Knowledge**	
TRA-1.D Explain the relationship between macroscopic characteristics and bond interactions for: a. Chemical processes. b. Physical processes.	**TRA-1.D.1** Processes that involve the breaking and/or formation of chemical bonds are typically classified as chemical processes. Processes that involve only changes in intermolecular interactions, such as phase changes, are typically classified as physical processes.	13-14; 95-97; 127-130; 253-254; 372-373, 380-382; 472, 502-516
	TRA-1.D.2 Sometimes physical processes involve the breaking of chemical bonds. For example, plausible arguments could be made for the dissolution of a salt in water, as either a physical or chemical process, involves breaking of ionic bonds, and the formation of ion-dipole interactions between ions and solvent.	125-127; 259- 262; 375-380; 529-531

Topic 4.5 Stoichiometry		
Enduring Understanding **SPQ-4** When a substance changes into a new substance, or when its properties change, no mass is lost or gained.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SPQ-4.A Explain changes in the amounts of reactants and products based on the balanced reaction equation for a chemical process.	**SPQ-4.A.1** Because atoms must be conserved during a chemical process, it is possible to calculate product amounts by using known reactant amounts, or to calculate reactant amounts given known product amounts.	100-112; 150-163
	SPQ-4.A.2 Coefficients of balanced chemical equations contain information regarding the proportionality of the amounts of substances involved in the reaction. These values can be used in chemical calculations involving the mole concept.	95-112; 129-132; 849-851
	SPQ-4.A.3 Stoichiometric calculations can be combined with the ideal gas law and calculations involving molarity to quantitatively study gases and solutions.	150-163; 196-199

Topic 4.6 Introduction to Titration		
Enduring Understanding **SPQ-4** When a substance changes into a new substance, or when its properties change, no mass is lost or gained.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SPQ-4.B Identify the equivalence point in a titration based on the amounts of the titrant and analyte, assuming the titration reaction goes to completion.	**SPQ-4.B.1** Titrations may be used to determine the concentration of an analyte in solution. The titrant has a known concentration of a species that reacts specifically and quantitatively with the analyte. The equivalence point of the titration occurs when the analyte is totally consumed by the reacting species in the titrant. The equivalence point is often indicated by a change in a property (such as color) that occurs when the equivalence point is reached. This observable event is called the endpoint of the titration.	157-163; 736-743

Topic 4.7 Types of Chemical Reactions		
Enduring Understanding **TRA-2** When a substance changes into a new substance, or when its properties change, no mass is lost or gained.		
Learning Objective	**Essential Knowledge**	**Page number**
TRA-2.A Identify a reaction as acid-base, oxidation-reduction, or precipitation.	**TRA-2.A.1** Acid-base reactions involve transfer of one or more protons between chemical species.	132-138; 673-676; 736-743
	TRA-2.A.2 Oxidation-reduction reactions involve transfer of one or more electrons between chemical species, as indicated by changes in oxidation numbers of the involved species. Combustion is an important subclass of oxidation-reduction reactions, in which a species reacts with oxygen gas. In the case of hydrocarbons, carbon dioxide and water are products of complete combustion.	138-150, 816-819
	TRA-2.A.3 In a redox reaction, electrons are transferred from the species that is oxidized to the species that is reduced.	138-141; 822-827
	TRA-2.A.4 Oxidation numbers may be assigned to each of the atoms in the reactants and products; this is often an effective way to identify the oxidized and reduced species in a redox reaction.	138-141; 822-827
	TRA-2.A.5 Precipitation reactions frequently involve mixing ions in aqueous solution to produce an insoluble or sparingly soluble ionic compound. All sodium, potassium, ammonium, and nitrate salts are soluble in water.	127-132, 155-157; 51528-531; 746-748, 764-767

Topic 4.8 Introduction to Acid-Base Reactions		
Enduring Understanding **TRA-2** When a substance changes into a new substance, or when its properties change, no mass is lost or gained.		
Learning Objective **TRA-2.B** Identify species as Brønsted-Lowry acids, bases, and/or conjugate acid-base pairs, based on proton-transfer involving those species.	**Essential Knowledge** **TRA-2.B.1** By definition, a Brønsted-Lowry acid is a proton donor and a Brønsted-Lowry base is a proton acceptor.	**Page numbers** 133-136; 673-674
	TRA-2.B.2 Only in aqueous solutions, water plays an important role in many acid-base reactions, as its molecular structure allows it to accept protons from and donate protons to dissolved species.	133-136; 673-676
	TRA-2.B.3 When an acid or base ionizes in water, the conjugate acid-base pairs can be identified and their relative strengths compared.	133-136; 673-676, 682-686

Topic 4.9 Oxidation-Reduction (Redox) Reactions		
Enduring Understanding **TRA-2** When a substance changes into a new substance, or when its properties change, no mass is lost or gained.		
Learning Objective **TRA-2.C** Represent a balanced redox reaction equation using half-reactions.	**Essential Knowledge** **TRA-2.C.1** Balanced chemical equations for redox reactions can be constructed from half-reactions..	**Page numbers** 138-150; 816-819, 846-849

Back to Table of Contents

Unit 5: Kinetics

<table>
<tr><td colspan="3">Topic 5.1 Reaction Rates</td></tr>
<tr><td colspan="3">Enduring Understanding
TRA-3 Some reactions happen quickly, while others happen more slowly and depend on reactant concentrations and temperature.</td></tr>
<tr><td rowspan="3">Learning Objective
TRA-3.A Explain the relationship between the rate of a chemical reaction and experimental parameters.</td><td>Essential Knowledge
TRA-3.A.1 The kinetics of a chemical reaction is defined as the rate at which an amount of reactants is converted to products per unit of time.</td><td>Page numbers
568-571</td></tr>
<tr><td>TRA-3.A.2 The rates of change of reactant and product concentrations are determined by the stoichiometry in the balanced chemical equation.</td><td>573-575</td></tr>
<tr><td>TRA-3.A.3 The rate of a reaction is influenced by reactant concentrations, temperature, surface area, catalysts, and other environmental factors.</td><td>570-600, 607-614</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 5.2 Introduction to Rate Law</td></tr>
<tr><td colspan="3">Enduring Understanding
TRA-3 Some reactions happen quickly, while others happen more slowly and depend on reactant concentrations and temperature.</td></tr>
<tr><td rowspan="5">Learning Objective
TRA-3.B Represent experimental data with a consistent rate law expression.</td><td>Essential Knowledge
TRA-3.B.1 Experimental methods can be used to monitor the amounts of reactants and/or products of a reaction and to determine the rate of the reaction.</td><td>Page numbers
569-573, 576-580</td></tr>
<tr><td>TRA-3.B.2 The rate law expresses the rate of a reaction as proportional to the concentration of each reactant raised to a power.</td><td>576-592</td></tr>
<tr><td>TRA-3.B.3 The power of each reactant in the rate law is the order of the reaction with respect to that reactant. The sum of the powers of the reactant concentrations in the rate law is the overall order of the reaction.</td><td>579-592</td></tr>
<tr><td>TRA-3.B.4 The proportionality constant in the rate law is called the rate constant. The value of this constant is temperature dependent and the units reflect the overall reaction order.</td><td>572, 580-592</td></tr>
<tr><td>TRA-3.B.5 Comparing initial rates of a reaction is a method to determine the order with respect to each reactant.</td><td>570-575</td></tr>
</table>

Topic 5.3 Concentration Changes Over Time		
Enduring Understanding **TRA-3** Some reactions happen quickly, while others happen more slowly and depend on reactant concentrations and temperature.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-3.C Identify the rate law expression of a chemical reaction using data that show how the concentrations of reaction species change over time.	**TRA-3.C.1** The order of a reaction can be inferred from a graph of concentration of reactant versus time.	568-580, 592
	TRA-3.C.2 If a reaction is first order with respect to a reactant being monitored, a plot of the natural log (ln) of the reactant concentration as a function of time will be linear.	580-592, 579
	TRA-3.C.3 If a reaction is second order with respect to a reactant being monitored, a plot of the reciprocal of the concentration of that reactant versus time will be linear.	588-592
	TRA-3.C.4 The slopes of the concentration versus time data for zeroth, first, and second order reactions can be used to determine the rate constant for the reaction. Zeroth order: EQN: $[A]_t - [A]_0 = -kt$ First order: EQN: $\ln[A]_t - \ln[A]_0 = -kt$ Second order: EQN: $1/[A]_t - 1/[A]_0 = kt$	580-592
	TRA-3.C.5 Half-life is a critical parameter for first order reactions because the half-life is constant and related to the rate constant for the reaction by the equation: EQN: $t_{1/2} = 0.693/k$.	580-592; 874-877
	TRA-3.C.6 Radioactive decay processes provide an important illustration of first order kinetics	874-877

Topic 5.4 Elementary Reactions		
Enduring Understanding **TRA-4** There is a relationship between the speed of a reaction and the collision frequency of particle collisions.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-4.A Represent an elementary reaction as a rate law expression using stoichiometry.	**TRA-4.A.1** The rate law of an elementary reaction can be inferred from the stoichiometry of the molecules participating in a collision.	600-607
	TRA-4.A.2 Elementary reactions involving the simultaneous collision of three or more particles are rare.	600-601

Topic 5.5 Collision Model		
Enduring Understanding **TRA-4** There is a relationship between the speed of a reaction and the collision frequency of particle collisions.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-4.B Explain the relationship between the rate of an elementary reaction and the frequency, energy, and orientation of molecular collisions.	**TRA-4.B.1** For an elementary reaction to successfully produce products, reactants must successfully collide to initiate bond-breaking and bond-making events.	592-594, 600-607
	TRA-4.B.2 In most reactions, only a small fraction of the collisions leads to a reaction. Successful collisions have both sufficient energy to overcome energy barriers and orientations that allow the bonds to rearrange in the required manner.	592-607
	TRA-4.B.3 The Maxwell-Boltzmann distribution curve describes the distribution of particle energies; this distribution can be used to gain a qualitative estimate of the fraction of collisions with sufficient energy to lead to a reaction, and also how that fraction depends on temperature.	207-209; 592-594, 607-614

Topic 5.6 Reaction Energy Profile		
Enduring Understanding **TRA-4** There is a relationship between the speed of a reaction and the collision frequency of particle collisions.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-4.C Represent the activation energy and overall energy change in an elementary reaction using a reaction energy profile.	**TRA-4.C.1** Elementary reactions typically involve the breaking of some bonds and the forming of new ones.	600
	TRA-4.C.2 The reaction coordinate is the axis along which the complex set of motions involved in rearranging reactants to form products can be plotted.	568-572
	TRA-4.C.3 The energy profile gives the energy along the reaction coordinate, which typically proceeds from reactants, through a transition state, to products. The energy difference between the reactants and the transition state is the activation energy for the forward reaction.	592-600
	TRA-4.C.4 The Arrhenius equation relates the temperature dependence of the rate of an elementary reaction to the activation energy needed by molecular collisions to reach the transition state.	592-600

Topic 5.7 Introduction to Reaction Mechanisms		
Enduring Understanding **TRA-5** Many chemical reactions occur through a series of elementary reactions. These elementary reactions when combined form a chemical equation.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-5.A Identify the components of a reaction mechanism.	**TRA-5.A.1** A reaction mechanism consists of a series of elementary reactions, or steps, that occur in sequence. The components may include reactants, intermediates, products, and catalysts.	600-614
	TRA-5.A.2 The elementary steps when combined should align with the overall balanced equation of a chemical reaction.	600
	TRA-5.A.3 A reaction intermediate is produced by some elementary steps and consumed by others, such that it is present only while a reaction is occurring.	600-601
	TRA-5.A.4 Experimental detection of a reaction intermediate is a common way to build evidence in support of one reaction mechanism over an alternative mechanism.	600-607

Topic 5.8 Reaction Mechanism and Rate Law		
Enduring Understanding **TRA-5** Many chemical reactions occur through a series of elementary reactions. These elementary reactions when combined form a chemical equation.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-5.B Identify the rate law for a reaction from a mechanism in which the first step is rate limiting.	**TRA-5.B.1** For reaction mechanisms in which each elementary step is irreversible, or in which the first step is rate limiting, the rate law of the reaction is set by the molecularity of the slowest elementary step (i.e., the rate-limiting step).	600-607

Topic 5.9 Steady-State Approximation		
Enduring Understanding **TRA-5** Many chemical reactions occur through a series of elementary reactions. These elementary reactions when combined form a chemical equation.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-5.C Identify the rate law for a reaction from a mechanism in which the first step is not rate limiting.	**TRA-5.C.1** If the first elementary reaction is not rate limiting, approximations (such as steady state) must be made to determine a rate law expression.	600-607

Topic 5.10 Multistep Reaction Energy Profile		
Enduring Understanding **TRA-5** Many chemical reactions occur through a series of elementary reactions. These elementary reactions when combined form a chemical equation.		
Learning Objective **TRA-5.D** Represent the activation energy and overall energy change in a multistep reaction with a reaction energy profile.	**Essential Knowledge** **TRA-5.D.1** Knowledge of the energetics of each elementary reaction in a mechanism allows for the construction of an energy profile for a multistep reaction.	**Page numbers** 592-593, 601-605, 608

Topic 5.11 Catalysis		
Enduring Understanding **ENE-1** Many chemical reactions occur through a series of elementary reactions. These elementary reactions when combined form a chemical equation.		
Learning Objective **ENE-1.A** Explain the relationship between the effect of a catalyst on a reaction and changes in the reaction mechanism.	**Essential Knowledge** **ENE-1.A.1** In order for a catalyst to increase the rate of a reaction, the addition of the catalyst must increase the number of effective collisions and/ or provide a reaction path with a lower activation energy relative to the original reaction coordinate.	**Page numbers** 607-614; 656
	ENE-1.A.2 In a reaction mechanism containing a catalyst, the net concentration of the catalyst is constant. However, the catalyst will frequently be consumed in the rate-determining step of the reaction, only to be regenerated in a subsequent step in the mechanism.	607-608
	ENE-1.A.3 Some catalysts accelerate a reaction by binding to the reactant(s). The reactants are either oriented more favorably or react with lower activation energy. There is often a new reaction intermediate in which the catalyst is bound to the reactant(s). Many enzymes function in this manner.	607-614
	ENE-1.A.4 Some catalysts involve covalent bonding between the catalyst and the reactant(s). An example is acid-base catalysis, in which a reactant or intermediate either gains or loses a proton. This introduces a new reaction intermediate and new elementary reactions involving that intermediate.	607-614
	ENE-1.A.5 In surface catalysis, a reactant or intermediate binds to, or forms a covalent bond with, the surface. This introduces elementary reactions involving these new bound reaction intermediate(s).	607-610

Back to Table of Contents

Unit 6: Thermodynamics

Topic 6.1 Endothermic and Exothermic Processes		
Enduring Understanding **ENE-2** Changes in a substance's properties or change into a different substance requires an exchange of energy.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-2.A Explain the relationship between experimental observations and energy changes associated with a chemical or physical transformation.	**ENE-2.A.1** Temperature changes in a system indicate energy changes.	11; 232-234, 236-239, 259-262
	ENE-2.A.2 Energy changes in a system can be described as endothermic and exothermic processes such as the heating or cooling of a substance, phase changes, or chemical transformations.	11; 232-234
	ENE-2.A.3 When a chemical reaction occurs, the energy of the system either decreases (exothermic reaction), increases (endothermic reaction), or remains the same. For exothermic reactions, the energy lost by the reacting species (system) is gained by the surroundings, as heat transfer from or work done by the system. Likewise, for endothermic reactions, the system gains energy from the surroundings by heat transfer to or work done on the system.	11; 232-239, 246-249
	ENE-2.A.4 The formation of a solution may be an exothermic or endothermic process, depending on the relative strengths of intermolecular/interparticle interactions before and after the dissolution process.	259-262

Topic 6.2 Energy Diagrams		
Enduring Understanding **ENE-2** Changes in a substance's properties or change into a different substance requires an exchange of energy.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-2.B Represent a chemical or physical transformation with an energy diagram.	**ENE-2.B.1** A physical or chemical process can be described with an energy diagram that shows the endothermic or exothermic nature of that process.	233, 242, 259

Topic 6.3 Heat Transfer and Thermal Equilibrium		
Enduring Understanding **ENE-2** Changes in a substance's properties or change into a different substance requires an exchange of energy.		
Learning Objective **ENE-2.C** Explain the relationship between the transfer of thermal energy and molecular collisions.	**Essential Knowledge** **ENE-2.C.1** A physical or chemical process can be described with an energy diagram that shows the endothermic or exothermic nature of that process.	**Page numbers** 203-206; 231-232
	ENE-2.C.2 Collisions between particles in thermal contact can result in the transfer of energy. This process is called "heat transfer," "heat exchange," or "transfer of energy as heat."	203-206; 232-234, 238-243
	ENE-2.C.3 Eventually, thermal equilibrium is reached as the particles continue to collide. At thermal equilibrium, the average kinetic energy of both bodies is the same, and hence, their temperatures are the same.	231-232, 235-236

Topic 6.4 Heat Capacity and Calorimetry		
Enduring Understanding **ENE-2** Changes in a substance's properties or change into a different substance requires an exchange of energy.		
Learning Objective **ENE-2.D** Calculate the heat *q* absorbed or released by a system undergoing heating/ cooling based on the amount of the substance, the heat capacity, and the change in temperature.	**Essential Knowledge** **ENE-2.D.1** The heating of a cool body by a warmer body is an important form of energy transfer between two systems. The amount of heat transferred between two bodies may be quantified by the heat transfer equation: EQN: $q = mc\Delta T$. Calorimetry experiments are used to measure the transfer of heat.	**Page numbers** 247-249
	ENE-2.D.2 The first law of thermodynamics states that energy is conserved in chemical and physical processes.	235
	ENE-2.D.3 The transfer of a given amount of thermal energy will not produce the same temperature change in equal masses of matter with differing specific heat capacities.	247
	ENE-2.D.4 Heating a system increases the energy of the system, while cooling a system decreases the energy of the system.	235-242
	ENE-2.D.5 The specific heat capacity of a substance and the molar heat capacity are both used in energy calculations.	247-250
	ENE-2.D.6 Chemical systems change their energy through three main processes: heating/cooling, phase transitions, and chemical reactions.	231-234, 240-244; 502-511

Topic 6.5 Energy of Phase Changes		
Enduring Understanding **ENE-2** Changes in a substance's properties or change into a different substance requires an exchange of energy.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-2.E Explain changes in the heat *q* absorbed or released by a system undergoing a phase transition based on the amount of the substance in moles and the molar enthalpy of the phase transition.	**ENE-2.E.1** Energy must be transferred to a system to cause a substance to melt (or boil). The energy of the system therefore increases as the system undergoes a solid-to-liquid (or liquid-to-gas) phase transition. Likewise, a system releases energy when it freezes (or condenses). The energy of the system decreases as the system undergoes a liquid-to-solid (or gas-to-liquid) phase transition. The temperature of a pure substance remains constant during a phase change.	502-511
	ENE-2.E.2 The energy absorbed during a phase change is equal to the energy released during a complementary phase change in the opposite direction. For example, the molar heat of condensation of a substance is equal to the negative of its molar heat of vaporization.	502-511

Topic 6.6 Introduction to Enthalpy of Reaction		
Enduring Understanding **ENE-2** Changes in a substance's properties or change into a different substance requires an exchange of energy.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-2.F Calculate the heat q absorbed or released by a system undergoing a chemical reaction in relationship to the amount of the reacting substance in moles and the molar enthalpy of reaction.	**ENE-2.F.1** The enthalpy change of a reaction gives the amount of heat energy released (for negative values) or absorbed (for positive values) by a chemical reaction at constant pressure.	242-243

Topic 6.7 Bond Enthalpies		
Enduring Understanding **ENE-3** The energy exchanged in a chemical transformation is required to break and form bonds.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-3.A Calculate the enthalpy change of a reaction based on the average bond energies of bonds broken and formed in the reaction.	**ENE-3.A.1** During a chemical reaction, bonds are broken and/or formed, and these events change the potential energy of the system.	231-232; 403-408
	ENE-3.A.2 The average energy required to break all of the bonds in the reactant molecules can be estimated by adding up the average bond energies of all the bonds in the reactant molecules. Likewise, the average energy released in forming the bonds in the product molecules can be estimated. If the energy released is greater than the energy required, the reaction is exothermic. If the energy required is greater than the energy released, the reaction is endothermic.	358-361; 403-408

Topic 6.8 Enthalpy of Formation		
Enduring Understanding **ENE-3** The energy exchanged in a chemical transformation is required to break and form bonds.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-3.B Calculate the enthalpy change for a chemical or physical process based on the standard enthalpies of formation.	**ENE-3.B.1** Tables of standard enthalpies of formation can be used to calculate the standard enthalpies of reactions. EQN: $\Delta H^\circ_{reaction} = \Sigma\Delta H^\circ_{f\ products} - \Sigma\Delta H^\circ_{f\ reactants}$	253-260

Topic 6.9 Hess's Law		
Enduring Understanding **ENE-3** The energy exchanged in a chemical transformation is required to break and form bonds.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-3.C Represent a chemical or physical process as a sequence of steps.	**ENE-3.C.1** Although the concept of "state function" is not required for the course, two principles of Hess's law should be understood. First, when a reaction is reversed, the enthalpy change stays constant in magnitude but becomes reversed in mathematical sign. Second, when two (or more) reactions are added to obtain an overall reaction, the individual enthalpy changes of each reaction are added to obtain the net enthalpy of the overall reaction.	253-260
ENE-3.D Explain the relationship between the enthalpy of a chemical or physical process and the sum of the enthalpies of the individual steps.	**ENE-3.D.1** When the products of a reaction are at a different temperature than their surroundings, they exchange energy with the surroundings to reach thermal equilibrium. Thermal energy is transferred to the surroundings from the products of an exothermic reaction. Thermal energy is transferred from the surroundings to the products of an endothermic reaction.	231-234; 655-656

Back to Table of Contents

Unit 7: Equilibrium

Topic 7.1 Introduction to Equilibrium		
Enduring Understanding **TRA-6** Some reactions can occur in both forward and reverse directions, sometimes proceeding in each direction simultaneously		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-6.A Explain the relationship between the occurrence of a reversible chemical or physical process, and the establishment of equilibrium, to experimental observations.	**TRA-6.A.1** Many observable processes are reversible. Examples include evaporation and condensation of water, absorption and desorption of a gas, or dissolution and precipitation of a salt. Some important reversible chemical processes include the transfer of protons in acid-base reactions and the transfer of electrons in redox reactions.	125-129, 133-134, 136-138; 208-210; 502-508; 538-541; 673-674; 746-753, 753-754; 816-8819
	TRA-6.A.2 When equilibrium is reached, no observable changes occur in the system. Reactants and products are simultaneously present, and the concentrations or partial pressures of all species remain constant.	630-633, 647-648
	TRA-6.A.3 The equilibrium state is dynamic. The forward and reverse processes continue to occur at equal rates, resulting in no net observable change.	503; 630-633
	TRA-6.A.4 Graphs of concentration, partial pressure, or rate of reaction versus time for simple chemical reactions can be used to understand the establishment of chemical equilibrium.	569, 571, 572, 573; 631, 653, 659

Topic 7.2 Direction of Reversible Reactions		
Enduring Understanding **TRA-6** Some reactions can occur in both forward and reverse directions, sometimes proceeding in each direction simultaneously		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-6.B Explain the relationship between the direction in which a reversible reaction proceeds and the relative rates of the forward and reverse reactions.	**TRA-6.B.1** If the rate of the forward reaction is greater than the reverse reaction, then there is a net conversion of reactants to products. If the rate of the reverse reaction is greater than that of the forward reaction, then there is a net conversion of products to reactants. An equilibrium state is reached when these rates are equal.	630-633, 644-646

<table>
<tr><td colspan="3">Topic 7.3 Reaction Quotient and Equilibrium Constant</td></tr>
<tr><td colspan="3">Enduring Understanding
TRA-7 A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.</td></tr>
<tr><td rowspan="2">Learning Objective
TRA-7.A Represent the reaction quotient Q_c or Q_p , for a reversible reaction, and the corresponding equilibrium expressions $K_c = Q_c$ or $K_p = Q_p$</td><td>Essential Knowledge
TRA-7.A.1 The reaction quotient Q_c describes the relative concentrations of reaction species at any time. For gas phase reactions, the reaction quotient may instead be written in terms of pressures as Q_p . The reaction quotient tends toward the equilibrium constant such that at equilibrium
$K_c = Q_c$ and $K_p = Q_p$.</td><td>Page numbers
647-651</td></tr>
<tr><td>TRA-7.A.2 The reaction quotient does not include substances whose concentrations (or partial pressures) are independent of the amount, such as for solids and pure liquids.</td><td>633-651</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 7.4 Calculating the Equilibrium Constant</td></tr>
<tr><td colspan="3">Enduring Understanding
TRA-7 A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.</td></tr>
<tr><td>Learning Objective
TRA-7.B Calculate K_c or K_p based on experimental observations of concentrations or pressures at equilibrium.</td><td>Essential Knowledge
TRA-7.B.1 Equilibrium constants can be determined from experimental measurements of the concentrations or partial pressures of the reactants and products at equilibrium.</td><td>Page numbers
630-644; 691-692; 749</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 7.5 Magnitude of the Equilibrium Constant</td></tr>
<tr><td colspan="3">Enduring Understanding
TRA-7 A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.</td></tr>
<tr><td>Learning Objective
TRA-7.C Explain the relationship between very large or very small values of K and the relative concentrations of chemical species at equilibrium.</td><td>Essential Knowledge
TRA-7.C.1 Some equilibrium reactions have very large K values and proceed essentially to completion. Others have very small K values and barely proceed at all.</td><td>Page numbers
632, 644-646</td></tr>
</table>

Topic 7.6 Magnitude of the Equilibrium Constant		
Enduring Understanding **TRA-7** A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.		
Learning Objective **TRA-7.D** Represent a multistep process with an overall equilibrium expression, using the constituent K expressions for each individual reaction.	**Essential Knowledge** **TRA-7.D.1** When a reaction is reversed, K is inverted.	**Page numbers** 642
	TRA-7.D.2 When the stoichiometric coefficients of a reaction are multiplied by a factor c, K is raised to the power c.	642-643
	TRA-7.D.3 When reactions are added together, the K of the resulting overall reaction is the product of the K's for the reactions that were summed.	642-643
	TRA-7.D.4 Since the expressions for K and Q have identical mathematical forms, all valid algebraic manipulations of K also apply to Q.	646-651

Topic 7.7 Calculating Equilibrium Concentrations		
Enduring Understanding **TRA-7** A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.		
Learning Objective **TRA-7.E** Identify the concentrations or partial pressures of chemical species at equilibrium based on the initial conditions and the equilibrium constant.	**Essential Knowledge** **TRA-7.E.1** The concentrations or partial pressures of species at equilibrium can be predicted given the balanced reaction, initial concentrations, and the appropriate K.	**Page numbers** 630-633, 637-638, 647-651; 676-682, 687-701, 705-710; 726-743, 746-755

Topic 7.8 Representations of Equilibrium		
Enduring Understanding **TRA-7** A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.		
Learning Objective **TRA-7.F** Represent a system undergoing a reversible reaction with a particulate model.	**Essential Knowledge** **TRA-7.F.1** Particulate representations can be used to describe the relative numbers of reactant and product particles present prior to and at equilibrium, and the value of the equilibrium constant.	**Page numbers** 639, 651, 654, 662, 665, 668; 683, 701, 710; 753

Topic 7.9 Introduction to Le Châtelier's Principle		
Enduring Understanding **TRA-8** Systems at equilibrium respond to external stresses to offset the effect of the stress.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-8.A Identify the response of a system at equilibrium to an external stress, using Le Châtelier's principle.	**TRA 8.A.1** Le Châtelier's principle can be used to predict the response of a system to stresses such as addition or removal of a chemical species, change in temperature, change in volume/ pressure of a gas-phase system, or dilution of a reaction system.	651-658
	TRA 8.A.2 Le Châtelier's principle can be used to predict the effect that a stress will have on experimentally measurable properties such as pH, temperature, and color of a solution.	651-658; 729-743, 755-758

Topic 7.10 Reaction Quotient and Le Châtelier's Principle		
Enduring Understanding **TRA-8** Systems at equilibrium respond to external stresses to offset the effect of the stress.		
Learning Objective	**Essential Knowledge**	**Page numbers**
TRA-8.B Explain the relationships between Q, K, and the direction in which a reversible reaction will proceed to reach equilibrium.	**TRA 8.B.1** A disturbance to a system at equilibrium causes Q to differ from K, thereby taking the system out of equilibrium. The system responds by bringing Q back into agreement with K, thereby establishing a new equilibrium state.	647-651
	TRA 8.B.2 Some stresses, such as changes in concentration, cause a change in Q only. A change in temperature causes a change in K. In either case, the concentrations or partial pressures of species redistribute to bring Q and K back into equality.	647-658

Topic 7.11 Introduction to Solubility Equilibria		
Enduring Understanding **SPQ-5** The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SPQ-5.A Calculate the solubility of a salt based on the value of K_{sp} for the salt.	**SPQ-5.A.1** The dissolution of a salt is a reversible process whose extent can be described by K_{sp}, the solubility-product constant.	746-753
	SPQ-5.A.2 The solubility of a substance can be calculated from the K_{sp} for the dissolution process. This relationship can also be used to predict the relative solubility of different substances.	746-764
	SPQ-5.A.3 The solubility rules (see TRA-2.A.5) can be quantitatively related to K_{sp}, in which K_{sp} values >1 correspond to soluble salts	737-741

Topic 7.12 Common-Ion Effect		
Enduring Understanding **SPQ-5** The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.		
Learning Objective **SPQ-5.B** Identify the solubility of a salt, and/or the value of K_{sp} for the salt, based on the concentration of a common ion already present in solution.	**Essential Knowledge** **SPQ-5.B.1** The solubility of a salt is reduced when it is dissolved into a solution that already contains one of the ions present in the salt. The impact of this "common-ion effect" on solubility can be understood qualitatively using Le Châtelier's principle or calculated from the K_{sp} for the dissolution process.	**Page numbers** 755-758

Topic 7.13 pH and Solubility		
Enduring Understanding **SPQ-5** The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.		
Learning Objective **SPQ-5.C** Identify the qualitative effect of changes in pH on the solubility of a salt.	**Essential Knowledge** **SPQ-5.C.1** The solubility of a salt is pH sensitive when one of the constituent ions is a weak acid or base. These effects can be understood qualitatively using Le Châtelier's principle	**Page numbers** 757-758

Topic 7.14 Free Energy of Dissolution		
Enduring Understanding **SPQ-5** The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.		
Learning Objective **SPQ-5.D** Explain the relationship between the solubility of a salt and changes in the enthalpy and entropy that occur in the dissolution process.	**Essential Knowledge** **SPQ-5.D.1** The free energy change ($\Delta G°$) for dissolution of a substance reflects a number of factors: the breaking of the intermolecular interactions that hold the solid together, the reorganization of the solvent around the dissolved species, and the interaction of the dissolved species with the solvent. It is possible to estimate the sign and relative magnitude of the enthalpic and entropic contributions to each of these factors. However, making predictions for the total change in free energy of dissolution can be challenging due to the cancellations among the free energies associated with the three factors cited.	**Page numbers** 259-262; 529-531; 782-784, 801-803

Back to Table of Contents

Unit 8: Acids and Bases

Topic 8.1 Introduction to Acids and Bases

Enduring Understanding

SAP-9 The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

Learning Objective	Essential Knowledge	Page numbers
SAP-9.A Calculate the values of pH and pOH, based on K_w and the concentration of all species present in a neutral solution of water.	**SAP-9.A.1** The concentrations of hydronium ion and hydroxide ion are often reported as pH and pOH, respectively. EQN: $pH = -\log[H_3O^+]$ EQN: $pOH = -\log[OH^-]$ The terms "hydrogen ion" and "hydronium ion" and the symbols $H^+(aq)$ and $H_3O^+(aq)$ are often used interchangeably for the aqueous ion of hydrogen. Hydronium ion and H_3O^+ (aq) are preferred, but H^+ (aq) is also accepted on the AP Exam.	132-133; 677-682; 757-758
	SAP-9.A.2 Water autoionizes with an equilibrium constant Kw. EQN: $K_w = [H_3O^+][OH^-] = 1.0 \times 10^{-14}$ at 25°C	674-676
	SAP-9.A.3 In pure water, pH = pOH is called a neutral solution. At 25°C, pK_w = 14.0 and thus pH = pOH = 7.0. EQN: $pK_w = 14 = pH + pOH$ at 25°C	677-682
	SAP-9.A.4 The value of Kw is temperature dependent, so the pH of pure, neutral water will deviate from 7.0 at temperatures other than 25°C.	675

Topic 8.2 Introduction to Acids and Bases

Enduring Understanding

SAP-9 The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

Learning Objective	Essential Knowledge	Page numbers
SAP-9.B Calculate pH and pOH based on concentrations of all species in a solution of a strong acid or a strong base	**SAP-9.B.1** Molecules of a strong acid (e.g., HCl, HBr, HI, $HClO_4$, H_2SO_4 , and HNO_3) will completely ionize in aqueous solution to produce hydronium ions. As such, the concentration of H_3O^+ in a strong acid solution is equal to the initial concentration of the strong acid, and thus the pH of the strong acid solution is easily calculated.	134-135; 683-686
	SAP-9.B.2 When dissolved in solution, strong bases (e.g., group I and II hydroxides) completely dissociate to produce hydroxide ions. As such, the concentration of OH^- in a strong base solution is equal to the initial concentration of the strong base, and thus the pOH (and pH) of the strong base solution is easily calculated.	134-135; 683-686

Topic 8.3 Weak Acid and Base Equilibria		
Enduring Understanding **SAP-9** The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-9.C Explain the relationship among pH, pOH, and concentrations of all species in a solution of a monoprotic weak acid or weak base.	**SAP-9.C.1** Weak acids react with water to produce hydronium ions. However, molecules of a weak acid will only partially ionize in this way. In other words, only a small percentage of the molecules of a weak acid are ionized in a solution. Thus, the concentration of H_3O^+ is much less than the initial concentration of the molecular acid, and the vast majority of the acid molecules remain un-ionized.	687, 701-715
	SAP-9.C.2 A solution of a weak acid involves equilibrium between an un-ionized acid and its conjugate base. The equilibrium constant for this reaction is K_a , often reported as pK_a . The pH of a weak acid solution can be determined from the initial acid concentration and the pK_a .	687-693, 697-701; 726-729
	SAP-9.C.3 Weak bases react with water to produce hydroxide ions in solution. However, ordinarily just a small percentage of the molecules of a weak base in solution will ionize in this way. Thus, the concentration of OH^- in the solution does not equal the initial concentration of the base, and the vast majority of the base molecules remain un-ionized.	693-694, 705-706, 710-715
	SAP-9.C.4 A solution of a weak base involves equilibrium between an un-ionized base and its conjugate acid. The equilibrium constant for this reaction is K_b , often reported as pK_b . The pH of a weak base solution can be determined from the initial base concentration and the pK_b .	693-697
	SAP-9.C.5 The percent ionization of a weak acid (or base) can be calculated from its pK_a (pK_b) and the initial concentration of the acid (base).	692-693

Topic 8.4 Acid-Base Reactions and Buffers

Enduring Understanding

SAP-9 The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

Learning Objective	Essential Knowledge	Page numbers
SAP-9.D Explain the relationship among the concentrations of major species in a mixture of weak and strong acids and bases.	**SAP-9.D.1** When a strong acid and a strong base are mixed, they react quantitatively in a reaction represented by the equation: $H^+ (aq) + OH^- (aq) \rightarrow H_2O(l)$. The pH of the resulting solution may be determined from the concentration of excess reagent.	136-137; 736-743
	SAP-9.D.2 When a weak acid and a strong base are mixed, they react quantitatively in a reaction represented by the equation: $HA(aq) + OH^- (aq)$ □ $A^- (aq)\ H_2O(l)$. If the weak acid is in excess, then a buffer solution is formed, and the pH can be determined from the Henderson-Hasselbalch (H-H) equation (see SAP-10.C.1). If the strong base is in excess, then the pH can be determined from the moles of excess hydroxide ion and the total volume of solution. If they are equimolar, then the (slightly basic) pH can be determined from the equilibrium represented by the equation: $A^-(aq) + H_2O(l)$ □ $HA(aq) + OH^- (aq)$.	738-741
	SAP-9.D.3 When a weak base and a strong acid are mixed, they will react quantitatively in a reaction represented by the equation: $B(aq) + H_3O^+ (aq)$ □ $HB^+(aq) + H_2O(l)$. If the weak base is in excess, then a buffer solution is formed, and the pH can be determined from the H-H equation. If the strong acid is in excess, then the pH can be determined from the moles of excess hydronium ion and the total volume of solution. If they are equimolar, then the (slightly acidic) pH can be determined from the equilibrium represented by the equation: $HB^+ (aq) + H_2O(l)$ □ $B(aq) + H_3O^+ (aq)$.	741-743
	SAP-9.D.4 When a weak acid and a weak base are mixed, they will react to an equilibrium state whose reaction may be represented by the equation: $HA(aq) + B(aq) \rightleftharpoons A^- (aq) + HB^+ (aq)$.	736

Topic 8.5 Acid-Base Titrations		
Enduring Understanding **SAP-9** The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-9.E Explain results from the titration of a mono- or polyprotic acid or base solution, in relation to the properties of the solution and its components.	**SAP-9.E.1** An acid-base reaction can be carried out under controlled conditions in a titration. A titration curve, plotting pH against the volume of titrant added, is useful for summarizing results from a titration	157-160; 736-743
	SAP-9.E.2 At the equivalence point, the number of moles of titrant added is equal to the number of moles of analyte originally present. This relationship can be used to obtain the concentration of the analyte. This is the case for titrations of strong acids/bases and weak acids/bases.	157-160; 736-743
	SAP-9.E.3 For titrations of weak acids/bases, it is useful to consider the point halfway to the equivalence point, that is, the half-equivalence point. At this point, there are equal concentrations of each species in the conjugate acid-base pair, for example, for a weak acid [HA] = [A^-]. Because pH = pK_a when the conjugate acid and base have equal concentrations, the pKa can be determined from the pH at the half-equivalence point in a titration.	769, 772
	SAP-9.D.4 For polyprotic acids, titration curves can be used to determine the number of acidic protons. In doing so, the major species present at any point along the curve can be identified, along with the pK_a associated with each proton in a weak polyprotic acid.	697-701; 775

Topic 8.6 Molecular Structure of Acids and Bases		
Enduring Understanding **SAP-9** The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-9.F Explain the relationship between the strength of an acid or base and the structure of the molecule or ion.	**SAP-9.F.1** The protons on a molecule that will participate in acid-base reactions, and the relative strength of these protons, can be inferred from the molecular structure. a. Strong acids (such as HCl, HBr, HI, HClO4 , H2 SO4 , and HNO3) have very weak conjugate bases that are stabilized by electronegativity, inductive effects, resonance, or some combination thereof. b. Carboxylic acids are one common class of weak acid. c. Strong bases (such as group I and II hydroxides) have very weak conjugate acids. d. Common weak bases include nitrogenous bases such as ammonia as well as carboxylate ions. e. Electronegative elements tend to stabilize the conjugate base relative to the conjugate acid, and so increase acid strength.	683-713; 1050-1051

Topic 8.7 pH and pK_a		
Enduring Understanding **SAP-10** A buffered solution resists changes to its pH when small amounts of acid or base are added.		
Learning Objective	**Essential Knowledge**	**Page numbers**
SAP-10.A Explain the relationship between the predominant form of a weak acid or base in solution at a given pH and the pK_a of the conjugate acid or the pK_b of the conjugate base.	**SAP-10.A.1** The protonation state of an acid or base (i.e., the relative concentrations of HA and A^-) can be predicted by comparing the pH of a solution to the pK_a of the acid in that solution. When solution pH < acid pK_a, the acid form has a higher concentration than the base form. When solution pH > acid pK_a, the base form has a higher concentration than the acid form.	687-697
	SAP-10.A.2 Acid-base indicators are substances that exhibit different properties (such as color) in their protonated versus deprotonated state, making that property respond to the pH of a solution.	743-746

Topic 8.8 Properties of Buffers		
Enduring Understanding **SAP-10** A buffered solution resists changes to its pH when small amounts of acid or base are added.		
Learning Objective **SAP-10.B** Explain the relationship between the ability of a buffer to stabilize pH and the reactions that occur when an acid or a base is added to a buffered solution.	**Essential Knowledge** **SAP-10.B.1** A buffer solution contains a large concentration of both members in a conjugate acid-base pair. The conjugate acid reacts with added base and the conjugate base reacts with added acid. These reactions are responsible for the ability of a buffer to stabilize pH.	**Page numbers** 729-730

Topic 8.9 Henderson-Hasselbalch Equation		
Enduring Understanding **SAP-10** A buffered solution resists changes to its pH when small amounts of acid or base are added.		
Learning Objective **SAP-10.C** Identify the pH of a buffer solution based on the identity and concentrations of the conjugate acid-base pair used to create the buffer.	**Essential Knowledge** **SAP-10.C.1** The pH of the buffer is related to the pK_a of the acid and the concentration ratio of the conjugate acid-base pair. This relation is a consequence of the equilibrium expression associated with the dissociation of a weak acid, and is described by the Henderson-Hasselbalch equation. Adding small amounts of acid or base to a buffered solution does not significantly change the ratio of $[A^-]/[HA]$ and thus does not significantly change the solution pH. The change in pH on addition of acid or base to a buffered solution is therefore much less than it would have been in the absence of the buffer.	**Page numbers** 726-729

Topic 8.10 Buffer Capacity		
Enduring Understanding **SAP-10** A buffered solution resists changes to its pH when small amounts of acid or base are added.		
Learning Objective **SAP-10.D** Explain the relationship between the buffer capacity of a solution and the relative concentrations of the conjugate acid and conjugate base components of the solution.	**Essential Knowledge** **SAP-10.D.1** Increasing the concentration of the buffer components (while keeping the ratio of these concentrations constant) keeps the pH of the buffer the same but increases the capacity of the buffer to neutralize added acid or base.	**Page numbers** 726-729
	SAP-10.D.2 When a buffer has more conjugate acid than base, it has a greater buffer capacity for addition of added base than acid. When a buffer has more conjugate base than acid, it has a greater buffer capacity for addition of added acid than base.	729-736

Back to Table of Contents

Unit 9: Applications of Thermodynamics

Topic 9.1 Introduction to Entropy		
Enduring Understanding **ENE-4** Some chemical or physical processes cannot occur without intervention.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-4.A Identify the sign and relative magnitude of the entropy change associated with chemical or physical processes.	**ENE-4.A.1** Entropy increases when matter becomes more dispersed. For example, the phase change from solid to liquid or from liquid to gas results in a dispersal of matter as the individual particles become freer to move and generally occupy a larger volume. Similarly, for a gas, the entropy increases when there is an increase in volume (at constant temperature), and the gas molecules are able to move within a larger space. For reactions involving gas-phase reactants or products, the entropy generally increases when the total number of moles of gas-phase products is greater than the total number of moles of gas-phase reactants.	780-786
	ENE-4.A.2 Entropy increases when energy is dispersed. According to kinetic molecular theory (KMT), the distribution of kinetic energy among the particles of a gas broadens as the temperature increases. As a result, the entropy of the system increases with an increase in temperature.	205-209; 780-786

Topic 9.2 Absolute Entropy and Entropy Change		
Enduring Understanding **ENE-4** Some chemical or physical processes cannot occur without intervention.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-4.B Calculate the entropy change for a chemical or physical process based on the absolute entropies of the species involved in the process.	**ENE-4.B.1** The entropy change for a process can be calculated from the absolute entropies of the species involved before and after the process occurs. EQN: $\Delta S^{o}_{reaction} = \Sigma S^{o}_{products} - \Sigma S^{o}_{reactants}$	786-791

<table>
<tr><td colspan="3">Topic 9.3 Gibbs Free Energy and Thermodynamic Favorability</td></tr>
<tr><td colspan="3">Enduring Understanding
ENE-4 Some chemical or physical processes cannot occur without intervention.</td></tr>
<tr><td rowspan="4">Learning Objective
ENE-4.C Explain whether a physical or chemical process is thermodynamically favored based on an evaluation of ΔG^o .</td><td>Essential Knowledge
ENE-4.C.1 The Gibbs free energy change for a chemical process in which all the reactants and products are present in a standard state (as pure substances, as solutions of 1.0 M concentration, or as gases at a pressure of 1.0 atm (or 1.0 bar)) is given the symbol ΔG^o .</td><td>Page numbers
794-795</td></tr>
<tr><td>ENE-4.C.2 The standard Gibbs free energy change for a chemical or physical process is a measure of thermodynamic favorability. Historically, the term “spontaneous” has been used to describe processes for which $\Delta G^o < 0$. The phrase “thermodynamically favored” is preferred instead so that common misunderstandings (equating “spontaneous” with “suddenly” or “without cause”) can be avoided. When $\Delta G^o < 0$ for the process, it is said to be thermodynamically favored.</td><td>792-794</td></tr>
<tr><td>ENE-4.C.3 The standard Gibbs free energy change for a physical or chemical process may also be determined from the standard Gibbs free energy of formation of the reactants and products.
EQN: $\Delta G^o_{reaction} = \Sigma \Delta G^o_{f\ products} - \Sigma \Delta G^o_{f\ reactants}$</td><td>792-795</td></tr>
<tr><td>ENE-4.C.4 In some cases, it is necessary to consider both enthalpy and entropy to determine if a process will be thermodynamically favored. The freezing of water and the dissolution of sodium nitrate are examples of such phenomena.</td><td>796-799</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 9.3 Gibbs Free Energy and Thermodynamic Favorability (continued)</td></tr>
<tr><td colspan="3">Enduring Understanding
ENE-4 Some chemical or physical processes cannot occur without intervention.</td></tr>
<tr><td rowspan="2">Learning Objective
ENE-4.C Explain whether a physical or chemical process is thermodynamically favored based on an evaluation of ΔG^o .</td><td>Essential Knowledge
ENE-4.C.5 Knowing the values of ΔH^o and ΔS^o for a process at a given temperature allows ΔG^o to be calculated directly.
EQN: $\Delta G^\circ = \Delta H^\circ - T\,\Delta S^\circ$</td><td>Page numbers
796-799</td></tr>
<tr><td>ENE-4.C.6 In general, the temperature conditions for a process to be thermodynamically favored ($\Delta G^o < 0$) can be predicted from the signs of ΔH^o and ΔS^o as shown in the table below:
<table>
<tr><td>ΔH^o</td><td>ΔS^o</td><td>Symbols</td><td>$\Delta G^o < 0$, favored at:</td></tr>
<tr><td>< 0</td><td>> 0</td><td>$< >$</td><td>all T</td></tr>
<tr><td>> 0</td><td>< 0</td><td>$> <$</td><td>no T</td></tr>
<tr><td>> 0</td><td>> 0</td><td>$> >$</td><td>high T</td></tr>
<tr><td>< 0</td><td>< 0</td><td>$< <$</td><td>low T</td></tr>
</table>

In cases where $\Delta H^o > 0$ and $\Delta S^o < 0$, no calculation of ΔG^o is necessary to determine that the process is thermodynamically unfavored ($\Delta G^o > 0$).</td><td>795-796</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 9.4 Thermodynamic and Kinetic Control</td></tr>
<tr><td colspan="3">Enduring Understanding
ENE-4 Some chemical or physical processes cannot occur without intervention.</td></tr>
<tr><td rowspan="2">Learning Objective
ENE-4.D Explain, in terms of kinetics, why a thermodynamically favored reaction might not occur at a measurable rate.</td><td>Essential Knowledge
ENE-4.D.1 Many processes that are thermodynamically favored do not occur to any measurable extent, or they occur at extremely slow rates.</td><td>Page numbers
778-779, 792-794, 795-796</td></tr>
<tr><td>ENE-4.D.2 Processes that are thermodynamically favored, but do not proceed at a measurable rate, are under “kinetic control.” High activation energy is a common reason for a process to be under kinetic control. The fact that a process does not proceed at a noticeable rate does not mean that the chemical system is at equilibrium. If a process is known to be thermodynamically favored, and yet does not occur at a measurable rate, it is reasonable to conclude that the process is under kinetic control.</td><td>593-596; 778-779</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 9.5 Free Energy and Equilibrium</td></tr>
<tr><td colspan="3">Enduring Understanding
ENE-5 The relationship between ΔG° and K can be used to determine favorability of a chemical or physical transformation.</td></tr>
<tr><td rowspan="4">Learning Objective
ENE-5.A Explain whether a process is thermodynamically favored using the relationships between K, ΔG^o , and T.</td><td>Essential Knowledge
ENE-5.A.1 The phrase “thermodynamically favored” ($\Delta G^o < 0$) means that the products are favored at equilibrium ($K > 1$).</td><td>Page numbers
801-803</td></tr>
<tr><td>ENE-5.A.2 The equilibrium constant is related to free energy by the equations
EQN: $K = e-\Delta G^\circ/RT$ and
EQN: $\Delta G^\circ = -RT \ln K$.</td><td>801-803</td></tr>
<tr><td>ENE-5.A.3 Connections between K and ΔG° can be made qualitatively through estimation. When ΔG° is near zero, the equilibrium constant will be close to 1. When ΔG° is much larger or much smaller than RT, the value of K deviates strongly from 1.</td><td>801-803</td></tr>
<tr><td>ENE-5.A.4 Processes with $\Delta G^\circ < 0$ favor products (i.e., $K > 1$) and those with $\Delta G^\circ > 0$ favor reactants (i.e., $K < 1$).</td><td>801-803</td></tr>
</table>

<table>
<tr><td colspan="3">Topic 9.6 Coupled Reactions</td></tr>
<tr><td colspan="3">Enduring Understanding
ENE-5 The relationship between ΔG° and K can be used to determine favorability of a chemical or physical transformation..</td></tr>
<tr><td rowspan="2">Learning Objective
ENE-5.B Explain the relationship between external sources of energy or coupled reactions and their ability to drive thermodynamically unfavorable processes.</td><td>Essential Knowledge
ENE-5.B.1 An external source of energy can be used to make a thermodynamically unfavorable process occur. Examples include: a. Electrical energy to drive an electrolytic cell or charge a battery. b. Light to drive the overall conversion of carbon dioxide to glucose in photosynthesis</td><td>Page numbers
801-803, 804-805</td></tr>
<tr><td>ENE-5.B.2 A desired product can be formed by coupling a thermodynamically unfavorable reaction that produces that product to a favorable reaction (e.g., the conversion of ATP to ADP in biological systems). In the coupled system, the individual reactions share one or more common intermediates. The sum of the individual reactions produces an overall reaction that achieves the desired outcome and has $\Delta G^\circ < 0$.</td><td>804-805</td></tr>
</table>

Topic 9.7 Galvanic (Voltaic) and Electrolytic Cells		
Enduring Understanding **ENE-6** Electrical energy can be generated by chemical reactions.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-6.A Explain the relationship between the physical components of an electrochemical cell and the overall operational principles of the cell.	**ENE-6.A.1** Each component of an electrochemical cell (electrodes, solutions in the half-cells, salt bridge, voltage/current measuring device) plays a specific role in the overall functioning of the cell. The operational characteristics of the cell (galvanic vs. electrolytic, direction of electron flow, reactions occurring in each half-cell, change in electrode mass, evolution of a gas at an electrode, ion flow through the salt bridge) can be described at both the macroscopic and particulate levels.	819-827
	ENE-6.A.2 Galvanic, sometimes called voltaic, cells involve a thermodynamically favored reaction, whereas electrolytic cells involve a thermodynamically unfavored reaction. Visual representations of galvanic and electrolytic cells are tools of analysis to identify where half-reactions occur and in what direction current flows.	820, 823, 836, 837, 838, 840, 841, 843, 846, 847
	ENE-6.A.3 For all electrochemical cells, oxidation occurs at the anode and reduction occurs at the cathode.	819-821, 836-840, 846-851

Topic 9.8 Cell Potential and Free Energy		
Enduring Understanding **ENE-6** Electrical energy can be generated by chemical reactions.		
Learning Objective	**Essential Knowledge**	**Page numbers**
ENE-6.B Explain the relationship between the physical components of an electrochemical cell and the overall operational principles of the cell.	**ENE-6.B.1** Electrochemistry encompasses the study of redox reactions that occur within electrochemical cells. The reactions are either thermodynamically favored (resulting in a positive voltage) or thermodynamically unfavored (resulting in a negative voltage and requiring an externally applied potential for the reaction to proceed).	816, 827-830
	ENE-6.B.2 The standard cell potential of electrochemical cells can be calculated by identifying the oxidation and reduction half-reactions and their respective standard reduction potentials.	822-827
	ENE-6.B.3 ΔG^o (standard Gibbs free energy change) is proportional to the negative of the cell potential for the redox reaction from which it is constructed. Thus, a cell with a positive E^o involves a thermodynamically favored reaction, and a cell with a negative E^o involves a thermodynamically unfavored reaction. EQN: $\Delta G^o = -nFE^o$	827-830

Topic 9.9 Cell Potential Under Nonstandard Conditions		
Enduring Understanding **ENE-6** Electrical energy can be generated by chemical reactions.		
Learning Objective **ENE-6.C** Explain the relationship between deviations from standard cell conditions and changes in the cell potential.	**Essential Knowledge** **ENE-6.C.1** In a real system under nonstandard conditions, the cell potential will vary depending on the concentrations of the active species. The cell potential is a driving force toward equilibrium; the farther the reaction is from equilibrium, the greater the magnitude of the cell potential.	**Page numbers** 822-835
	ENE-6.C.2 Equilibrium arguments such as Le Châtelier's principle do not apply to electrochemical systems, because the systems are not in equilibrium.	827-835
	ENE-6.C.3 The standard cell potential Eo corresponds to the standard conditions of Q = 1. As the system approaches equilibrium, the magnitude (i.e., absolute value) of the cell potential decreases, reaching zero at equilibrium (when Q = K). Deviations from standard conditions that take the cell further from equilibrium than Q = 1 will increase the magnitude of the cell potential relative to Eo . Deviations from standard conditions that take the cell closer to equilibrium than Q = 1 will decrease the magnitude of the cell potential relative to Eo . In concentration cells, the direction of spontaneous electron flow can be determined by considering the direction needed to reach equilibrium.	827-835
	ENE-6.C.4 Algorithmic calculations using the Nernst equation are insufficient to demonstrate an understanding of electrochemical cells under nonstandard conditions. However, students should qualitatively understand the effects of concentration on cell potential and use conceptual reasoning, including the qualitative use of the Nernst equation: EQN: $E = E^o - (RT/nF) \ln Q$ to solve problems.	831-835

Topic 9.10 Electrolysis and Faraday's Law		
Enduring Understanding **ENE-6** Electrical energy can be generated by chemical reactions.		
Learning Objective **ENE-6.D** Calculate the amount of charge flow based on changes in the amounts of reactants and products in an electrochemical cell.	**Essential Knowledge** **ENE-6.D.1** Faraday's laws can be used to determine the stoichiometry of the redox reaction occurring in an electrochemical cell with respect to the following: a. Number of electrons transferred b. Mass of material deposited on or removed from an electrode c. Current d. Time elapsed e. Charge of ionic species EQN: $I = q/t$	**Page numbers** 827-830, 846-851

Back to Table of Contents