Course at a Glance

Plan

The Course at a Glance provides a useful visual organization of the AP Chemistry curricular components, including:

- Sequence of units, along with approximate weighting and suggested pacing. Please note, pacing is based on 45-minute class periods, meeting five days each week for a full academic year.
- Progression of topics within each unit.
- Spiraling of the big ideas and science practices across units.

Teach

SCIENCE PRACTICES

Science practices spiral throughout the course.

1 Models and Representations
2 Question and Method
3 Representing Data and Phenomena
4 Model Analysis
5 Mathematical Routines
6 Argumentation

BIG IDEAS

Big ideas spiral across topics and units.

SPQ Scale, Proportion, and Quantity
SAP Structure and Properties
TRA Transformations
ENE Energy

Assess

Assign the Personal Progress Checks—either as homework or in class—for each unit. Each Personal Progress Check contains formative multiple-choice and free-response questions. The feedback from the Personal Progress Checks shows students the areas where they need to focus.

UNIT 1 Atomic Structure and Properties

~9–10 Class Periods | **7–9%** AP Exam Weighting

SPQ	5	**1.1** Moles and Molar Mass
SPQ	5	**1.2** Mass Spectroscopy of Elements
SPQ	2	**1.3** Elemental Composition of Pure Substances
SPQ	5	**1.4** Composition of Mixtures
SAP	1	**1.5** Atomic Structure and Electron Configuration
SAP	4	**1.6** Photoelectron Spectroscopy
SAP	4	**1.7** Periodic Trends
SAP	4	**1.8** Valence Electrons and Ionic Compounds

Personal Progress Check 1

Multiple-choice: ~20 questions
Free-response: 2 questions

- Short-answer
- Short-answer

UNIT 2 Molecular and Ionic Compound Structure and Properties

~12–13 Class Periods | **7–9%** AP Exam Weighting

SAP	6	**2.1** Types of Chemical Bonds
SAP	3	**2.2** Intramolecular Force and Potential Energy
SAP	4	**2.3** Structure of Ionic Solids
SAP	4	**2.4** Structure of Metals and Alloys
SAP	3	**2.5** Lewis Diagrams
SAP	6	**2.6** Resonance and Formal Charge
SAP	6	**2.7** VSEPR and Bond Hybridization

Personal Progress Check 2

Multiple-choice: ~15 questions
Free-response: 1 question

- Long-answer

continued on next page

UNIT 3 Intermolecular Forces and Properties

~14–15 Class Periods | **18–22%** AP Exam Weighting

SAP	4	3.1	Intermolecular Forces
SAP	4	3.2	Properties of Solids
SAP	3	3.3	Solids, Liquids, and Gases
SAP	5	3.4	Ideal Gas Law
SAP	4	3.5	Kinetic Molecular Theory
SAP	6	3.6	Deviation from Ideal Gas Law
SPQ	5	3.7	Solutions and Mixtures
SPQ	3	3.8	Representations of Solutions
SPQ	2	3.9	Separation of Solutions and Mixtures Chromatography
SPQ	4	3.10	Solubility
SAP	4	3.11	Spectroscopy and the Electromagnetic Spectrum
SAP	5	3.12	Photoelectric Effect
SAP	2	3.13	Beer-Lambert Law

Personal Progress Check 3

Multiple-choice: ~30 questions
Free-response: 2 questions

- Short-answer
- Short-answer

UNIT 4 Chemical Reactions

~14–15 Class Periods | **7–9%** AP Exam Weighting

TRA	2	4.1	Introduction for Reactions
TRA	5	4.2	Net Ionic Equations
TRA	3	4.3	Representations of Reactions
TRA	6	4.4	Physical and Chemical Changes
SPQ	5	4.5	Stoichiometry
SPQ	3	4.6	Introduction to Titration
TRA	1	4.7	Types of Chemical Reactions
TRA	1	4.8	Introduction to Acid-Base Reactions
TRA	5	4.9	Oxidation-Reduction (Redox) Reactions

Personal Progress Check 4

Multiple-choice: ~20 questions
Free-response: 1 question

- Long-answer

UNIT 5 Kinetics

~13–14 Class Periods | **7–9%** AP Exam Weighting

TRA	6	5.1	Reaction Rates
TRA	5	5.2	Introduction to Rate Law
TRA	5	5.3	Concentration Changes Over Time
TRA	5	5.4	Elementary Reactions
TRA	6	5.5	Collision Model
TRA	3	5.6	Reaction Energy Profile
TRA	1	5.7	Introduction to Reaction Mechanisms
TRA	5	5.8	Reaction Mechanism and Rate Law
TRA	5	5.9	Steady-State Approximation
TRA	3	5.10	Multistep Reaction Energy Profile
ENE	6	5.11	Catalysis

Personal Progress Check 5

Multiple-choice: ~25 questions
Free-response: 2 questions

- Short-answer
- Long-answer

continued on next page

UNIT 6 Thermodynamics

~10–11 Class Periods | **7–9%** AP Exam Weighting

ENE 6	**6.1**	Endothermic and Exothermic Processes
ENE 3	**6.2**	Energy Diagrams
ENE 6	**6.3**	Heat Transfer and Thermal Equilibrium
ENE 2	**6.4**	Heat Capacity and Calorimetry
ENE 1	**6.5**	Energy of Phase Changes
ENE 4	**6.6**	Introduction to Enthalpy of Reaction
ENE 5	**6.7**	Bond Enthalpies
ENE 5	**6.8**	Enthalpy of Formation
ENE 5	**6.9**	Hess's Law

Personal Progress Check 6

Multiple-choice: ~20 questions
Free-response: 2 questions
- Short-answer
- Short-answer

UNIT 7 Equilibrium

~14–16 Class Periods | **7–9%** AP Exam Weighting

TRA 6	**7.1**	Introduction to Equilibrium
TRA 4	**7.2**	Direction of Reversible Reactions
TRA 3	**7.3**	Reaction Quotient and Equilibrium Constant
TRA 5	**7.4**	Calculating the Equilibrium Constant
TRA 6	**7.5**	Magnitude of the Equilibrium Constant
TRA 5	**7.6**	Properties of the Equilibrium Constant
TRA 3	**7.7**	Calculating Equilibrium Concentrations
TRA 3	**7.8**	Representations of Equilibrium
TRA 6	**7.9**	Introduction to Le Châtelier's Principle
TRA 5	**7.10**	Reaction Quotient and Le Châtelier's Principle
SPQ 5	**7.11**	Introduction to Solubility Equilibria
SPQ 2	**7.12**	Common-Ion Effect
SPQ 2	**7.13**	pH and Solubility
SPQ 4	**7.14**	Free Energy of Dissolution

Personal Progress Check 7

Multiple-choice: ~30 questions
Free-response: 2 questions
- Short-answer
- Long-answer

UNIT 8 Acids and Bases

~14–15 Class Periods | **11–15%** AP Exam Weighting

SAP 5	**8.1**	Introduction to Acids and Bases
SAP 5	**8.2**	pH and pOH of Strong Acids and Bases
SAP 5	**8.3**	Weak Acid and Base Equilibria
SAP 5	**8.4**	Acid-Base Reactions and Buffers
SAP 5	**8.5**	Acid-Base Titrations
SAP 6	**8.6**	Molecular Structure of Acids and Bases
SAP 2	**8.7**	pH and pK_a
SAP 6	**8.8**	Properties of Buffers
SAP 5	**8.9**	Henderson-Hasselbalch Equation
SAP 6	**8.10**	Buffer Capacity

Personal Progress Check 8

Multiple-choice: ~30 questions
Free-response: 1 question
- Long-answer

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UNIT 9 Applications of Thermodynamics

~10–13 Class Periods | **7–9%** AP Exam Weighting

Personal Progress Check 9

Multiple-choice: ~30 questions

Free-response: 2 questions

- Short-answer
- Long-answer

AP CHEMISTRY

UNIT 1

Atomic Structure and Properties

7–9%
AP EXAM WEIGHTING

~9–10
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 1

Multiple-choice: ~20 questions
Free-response: 2 questions

- Short-answer
- Short-answer

UNIT 1 **7–9%** AP EXAM WEIGHTING **~9–10** CLASS PERIODS

Atomic Structure and Properties

BIG IDEA 1
Scale, Proportion, and Quantity **SPQ**

- Why are eggs sold as a dozen?

BIG IDEA 2
Structure and Properties **SAP**

- How can the same element be used in nuclear fuel rods and fake diamonds?

Developing Understanding

This first unit sets the foundation for the course by examining the atomic theory of matter, the fundamental premise of chemistry. Although atoms represent the foundational level of chemistry, observations of chemical properties are made on collections of atoms. Macroscopic systems involve such large numbers that they require moles as a unit of comparison. The periodic table provides information about each element's predictable periodicity as a function of the atomic number. The electronic structure of an atom can be described by an electron configuration that provides a method for describing the distribution of electrons in an atom or ion. In subsequent units, students will apply their understanding of atomic structure to models and representations of chemical phenomena and explain changes and interactions of chemical substances.

Building the Science Practices

1.A 2.A 4.A 4.B 4.C 5.A 5.B 5.D

In Unit 1, students will practice identifying components of commonly used models and representations to illustrate chemical phenomena. They will construct models and representations and explain whether they are consistent with chemical theories. Students will also practice translating between data and various representations (e.g., photoelectron spectroscopy data and electron configurations). Students should then be able to use representations (e.g., PES graphs, electron configurations, periodic table, drawings) to explain atomic structure, which is the foundation for all subsequent units.

Many of the most useful concepts in chemistry relate to patterns in the behavior of chemical systems, such as periodic trends in atomic and molecular properties. In this unit and all subsequent units, students should learn to analyze data presented graphically to identify patterns and relationships. Once a pattern is identified, students should be able to examine evidence to determine if it supports the pattern or hypothesis pertaining to a testable question.

Preparing for the AP Exam

On the AP Exam, students must be able to justify claims with evidence. This starts when students can identify the evidence needed to solve a problem or support a claim and then connect that evidence to known chemical theories. However, many students consistently demonstrate difficulty with this skill. For example, while students can memorize periodic trends, they struggle to explain the electrostatic interactions within an atom that produces period trends as well as exceptions to these trends. Further, students often have difficulty connecting periodic trends to the shell model, Coulomb's law, and elements of quantum theory.
To combat these challenges, teachers can ensure that students have a strong foundation in identifying mathematical relationships or patterns from graphical or tabular information and that they can explain how those patterns are consistent with chemical theories and models.

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods **~9–10** CLASS PERIODS
SPQ-1	**1.1 Moles and Molar Mass**	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	1.2 Mass Spectroscopy of Elements	**5.D** Identify information presented graphically to solve a problem.	
SPQ-2	**1.3 Elemental Composition of Pure Substances**	**2.A** Identify a testable scientific question based on an observation, data, or a model.	
	1.4 Composition of Mixtures	**5.A** Identify quantities needed to solve a problem from given information (e.g., text, mathematical expressions, graphs, or tables).	
SAP-1	**1.5 Atomic Structure and Electron Configuration**	**1.A** Describe the components of and quantitative information from models and representations that illustrate particulate-level properties only.	
	1.6 Photoelectron Spectroscopy	**4.B** Explain whether a model is consistent with chemical theories.	
SAP-2	**1.7 Periodic Trends**	**4.A** Explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.	
	1.8 Valence Electrons and Ionic Compounds	**4.C** Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 1.
Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	1.1	**Think-Pair-Share** Ask students to individually rank three samples in order of increasing number of particles, increasing mass, and increasing mole amounts (Sample A: 1.0 mole of carbon, Sample B: 18 grams of carbon monoxide, Sample C: 3.0×10^{23} molecules of water). Then have them compare and defend their choices with a partner.
2	1.2	**Simulations** Conduct a simulation of a mass spectrometer, using a strong magnet and steel ball bearings of various masses, to show students how mass can be used to separate particles based on their ability to be manipulated in an electromagnetic field. Present samples of mass spectra for students to analyze and have them calculate the average atomic mass of an element. Discuss how mass spectrometry could be used to identify the presence of an element within a mixture and the isotopic abundance within an element. Forensic science applications and other modern uses of the technology can be discussed to give relevant context to the concepts.
3	1.3	**Think-Pair-Share** Have students design an experiment to determine the percent composition of a mixture of sodium carbonate (inert) and sodium bicarbonate. After carrying out the experiment, provide them with a mock student report to analyze and critique. Then have them get into pairs and reflect on their particular approach and come up with additional approaches to this problem.
4	1.4 1.5	**Explore Representations** Translate PES data into an electron configuration and/or predict a PES spectrum based on an element's electron configuration or location in the periodic table. Have students compare their predictions to the actual electron configuration and discuss discrepancies.
5	1.6	**Process Oriented Guided Inquiry Learning (POGIL)** Given ionization energy data from various elements, guide students through a series of questions to help them rationalize the relationship of the charge of the ion to its position on the periodic table, its electronic structure, and reactivity.

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**
- AP Chemistry Lab Manual > **Investigation 3: What Makes Hard Water Hard?**
- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 1**

TOPIC 1.1

Moles and Molar Mass

Required Course Content

ENDURING UNDERSTANDING

SPQ-1

The mole allows different units to be compared.

LEARNING OBJECTIVE

SPQ-1.A

Calculate quantities of a substance or its relative number of particles using dimensional analysis and the mole concept.

ESSENTIAL KNOWLEDGE

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.

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.

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: $n = m/M$

TOPIC 1.2

Mass Spectroscopy of Elements

Required Course Content

ENDURING UNDERSTANDING

SPQ-1

The mole allows different units to be compared.

LEARNING OBJECTIVE

SPQ-1.B

Explain the quantitative relationship between the mass spectrum of an element and the masses of the element's isotopes.

ESSENTIAL KNOWLEDGE

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.

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.

☒ INTERPRETING MASS SPECTRA

Interpreting mass spectra of samples containing multiple elements or peaks arising from species other than singly charged monatomic ions will not be assessed on the AP Exam.

SUGGESTED SKILL

Mathematical Routines

5.D

Identify information presented graphically to solve a problem.

AVAILABLE RESOURCES

- Classroom Resource > **Exploring Atomic Structure Using Photoelectron Spectroscopy (PES) Data**

SUGGESTED SKILL

Question and Method

2.A

Identify a testable scientific question based on an observation, data, or a model.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 3: What Makes Hard Water Hard?**

TOPIC 1.3

Elemental Composition of Pure Substances

Required Course Content

ENDURING UNDERSTANDING

SPQ-2

Chemical formulas identify substances by their unique combination of atoms.

LEARNING OBJECTIVE

SPQ-2.A

Explain the quantitative relationship between the elemental composition by mass and the empirical formula of a pure substance.

ESSENTIAL KNOWLEDGE

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.

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.

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.

TOPIC 1.4

Composition of Mixtures

Required Course Content

ENDURING UNDERSTANDING

SPQ-2

Chemical formulas identify substances by their unique combination of atoms.

LEARNING OBJECTIVE

SPQ-2.B

Explain the quantitative relationship between the elemental composition by mass and the composition of substances in a mixture.

ESSENTIAL KNOWLEDGE

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.

SPQ-2.B.2

Elemental analysis can be used to determine the relative numbers of atoms in a substance and to determine its purity.

SUGGESTED SKILL

Mathematical Routines

5.A

Identify quantities needed to solve a problem from given information (e.g., text, mathematical expressions, graphs, or tables).

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 1.5

Atomic Structure and Electron Configuration

SUGGESTED SKILL

Models and Representations

1.A

Describe the components of and quantitative information from models and representations that illustrate particulate-level properties only.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

Required Course Content

ENDURING UNDERSTANDING

SAP-1

Atoms and molecules can be identified by their electron distribution and energy.

LEARNING OBJECTIVE

SAP-1.A

Represent the electron configuration of an element or ions of an element using the Aufbau principle.

ESSENTIAL KNOWLEDGE

SAP-1.A.1

The atom is composed of negatively charged electrons and a positively charged nucleus that is made of protons and neutrons.

SAP-1.A.2

Coulomb's law is used to calculate the force between two charged particles.

EQN: $F_{coulombic} \propto \frac{q_1 q_2}{r^2}$

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.

☒ **THE ASSIGNMENT OF QUANTUM NUMBERS TO ELECTRONS IN SUBSHELLS OF AN ATOM WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Assignment of quantum numbers to electrons in specific subshells does not increase students' understanding of the structure of the atom.*

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LEARNING OBJECTIVE

SAP-1.A

Represent the electron configuration of an element or ions of an element using the Aufbau principle.

ESSENTIAL KNOWLEDGE

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.

SUGGESTED SKILL

Model Analysis

4.B

Explain whether a model is consistent with chemical theories.

AVAILABLE RESOURCES

- Classroom Resource > **Exploring Atomic Structure Using Photoelectron Spectroscopy (PES) Data**

TOPIC 1.6

Photoelectron Spectroscopy

Required Course Content

ENDURING UNDERSTANDING

SAP-1

Atoms and molecules can be identified by their electron distribution and energy.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

TOPIC 1.7

Periodic Trends

SUGGESTED SKILL

Model Analysis

4.A

Explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

Required Course Content

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.

☒ **WRITING THE ELECTRON CONFIGURATION OF ELEMENTS THAT ARE EXCEPTIONS TO THE AUFBAU PRINCIPLE WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *The mere rote recall of the exceptions does not match the goals of the curriculum revision.*

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.

SAP-2.A.3

The periodicity (in SAP-2.A.2) is useful to predict /estimate values of properties in the absence of data.

SUGGESTED SKILL

Model Analysis

4.C

Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

TOPIC 1.8

Valence Electrons and Ionic Compounds

Required Course Content

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.

SAP-2.B.2

Elements in the same column of the periodic table tend to form analogous compounds.

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.

AP CHEMISTRY

UNIT 2

Molecular and Ionic Compound Structure and Properties

7–9%
AP EXAM WEIGHTING

~12–13
CLASS PERIODS

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Personal Progress Check 2

Multiple-choice: ~15 questions
Free-response: 1 question

- Long-answer

UNIT 2 | **7–9%** AP EXAM WEIGHTING | **~12–13** CLASS PERIODS

Molecular and Ionic Compound Structure and Properties

BIG IDEA 2
Structure and Properties **SAP**

- How has the discovery of DNA changed the world?
- How are molecular compounds arranged?

Developing Understanding

In Unit 2, students apply their knowledge of atomic structure at the particulate level and connect it to the macroscopic properties of a substance. Both the chemical and physical properties of materials can be explained by the structure and arrangement of atoms, ions, or molecules and the forces between them. These forces, called chemical bonds, are distinct from typical intermolecular interactions. Electronegativity can be used to make predictions about the type of bonding present between two atoms. In subsequent units, students will use the periodic table and the atomic properties to predict the type of bonding present between two atoms based on position.

Building the Science Practices

3.A 3.B 4.C 6.A 6.C

In this unit, students will learn how to interpret simple graphical representations of changes in potential energy as two atoms approach each other to explain optimal bond length as well as why bonds may or may not occur. Students should also practice constructing representations and models for chemical phenomena (e.g., ionic and metallic solids) and using representations to make claims or predictions. For example, students can use VSEPR theory to draw Lewis structures of molecules and predict their three-dimensional geometry and polarity.

Instead of simply connecting chemical theories to phenomena occurring at the atomic level, it is important to provide explanations across scales. For example, teachers can ask students to explain the connection between electronegativity and ionization energy with the type of bond formed and the macroscopic properties of a particular substance. Students should also work with several chemical concepts (Coulomb's law, formal charge, and resonance) to evaluate the accuracy of a model in representing both the particulate-level structure and macroscopic observations. In future units, students will use the practice of constructing and understanding molecular representations to make predictions and claims about interparticle interactions, intermolecular forces, and their connections to macroscopic observations.

Preparing for the AP Exam

On the AP Exam, students must be able to construct Lewis structures and make predictions or claims based on them. However, students often struggle to predict the correct molecular shape or bond angle based on VSEPR and the use of formal charge. Mistakes include: using the incorrect number of valence electrons, violating the octet rule, or confusing molecular geometry with bond angles. Teachers can students with multiple opportunities to practice drawing Lewis electron-dot diagrams, including resonance structures. Students should also practice predicting and describing molecular shapes, bond angles, and polarities from Lewis structures, and calculating and connecting formal charges in Lewis structures to the predicted structure of a molecule.

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~12–13 CLASS PERIODS
SAP-3	**2.1 Types of Chemical Bonds**	**6.A** Make a scientific claim.	
	2.2 Intramolecular Force and Potential Energy	**3.A** Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.	
	2.3 Structure of Ionic Solids	**4.C** Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.	
	2.4 Structure of Metals and Alloys	**4.C** Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.	
SAP-4	**2.5 Lewis Diagrams**	**3.B** Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).	
	2.6 Resonance and Formal Charge	**6.C** Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.	
	2.7 VSEPR and Bond Hybridization	**6.C** Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 2. Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	2.2	**Think-Pair-Share** After a review of the graph of potential energy versus internuclear distance in a hydrogen molecule, have students pair up and describe what they believe the graph would look like for various other molecules.
2	2.3	**Explore Representations** Demonstrate a model of ionic bonding. Put opaque adhesive tape on top of disk magnets to make "+" and "–" signs. Be sure to affix the tape on opposite sides for the differing charges (so that opposite ions have opposite magnetic polarity when arranged on a flat surface). Arrange the ions in an alternating array on the overhead projector to show the structure of an ionic crystal. Engage students in a discussion about malleability/brittleness, and ask why distorting an ionic crystal causes shattering. This also introduces Coulombic forces in a visual and memorable way. Then have students predict and identify the bonding in binary compounds using periodic trends.
3	2.4	**Manipulatives** Have students use various sized/colored paper plates to illustrate a particular type of alloy (interstitial and/or substitutional). Then have them engage in a gallery walk around the room to listen to others explain the connection between the structure of the different alloys and the properties of each.
4	2.5 2.6 2.7	**Simulations** Construct various VSEPR shapes using balloons to show the three-dimensional arrangement of atoms in various bonding arrangements. Then use a PhET simulation to help students see the effects of lone pairs and bonding pairs on molecular shape. Students can work on this individually after being shown how to use the interface, or it can be projected and examined as a class. Have students work with the simulation to add/remove bonds and add/remove lone pairs to determine the most likely three-dimensional shape and bond angles in a molecule.

SUGGESTED SKILL

Argumentation

6.A

Make a scientific claim.

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 3**
- AP Chemistry Lab Manual > **Investigation 6: What's in That Bottle?**

TOPIC 2.1

Types of Chemical Bonds

Required Course Content

ENDURING UNDERSTANDING

SAP-3

Atoms or ions bond due to interactions between them, forming molecules.

LEARNING OBJECTIVE

SAP-3.A

Explain the relationship between the type of bonding and the properties of the elements participating in the bond.

ESSENTIAL KNOWLEDGE

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.

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.

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.

continued on next page

LEARNING OBJECTIVE

SAP-3.A

Explain the relationship between the type of bonding and the properties of the elements participating in the bond.

ESSENTIAL KNOWLEDGE

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.

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.

SUGGESTED SKILL

Representing Data and Phenomena

3.A

Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 5: Sticky Question: How Do You Separate Molecules That Are Attracted to One Another?**
- Classroom Resources > **Ending Misconceptions About the Energy of Chemical Bonds**

TOPIC 2.2

Intramolecular Force and Potential Energy

Required Course Content

ENDURING UNDERSTANDING

SAP-3

Atoms or ions bond due to interactions between them, forming molecules.

LEARNING OBJECTIVE

SAP-3.B

Represent the relationship between potential energy and distance between atoms, based on factors that influence the interaction strength.

ESSENTIAL KNOWLEDGE

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).

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.

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.

TOPIC 2.3

Structure of Ionic Solids

SUGGESTED SKILL

Model Analysis

4.C

Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.

AVAILABLE RESOURCES

- The Exam > **2017 Chief Reader Report**

Required Course Content

ENDURING UNDERSTANDING

SAP-3

Atoms or ions bond due to interactions between them, forming molecules.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

☒ **KNOWLEDGE OF SPECIFIC TYPES OF CRYSTAL STRUCTURES WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Study of specific crystal structures is not essential to an understanding of the big ideas.*

SUGGESTED SKILL

Model Analysis

4.C

Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.

AVAILABLE RESOURCES

- The Exam > **2017 Chief Reader Report**

TOPIC 2.4

Structure of Metals and Alloys

Required Course Content

ENDURING UNDERSTANDING

SAP-3

Atoms or ions bond due to interactions between them, forming molecules.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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").

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).

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.)

TOPIC 2.5

Lewis Diagrams

Required Course Content

ENDURING UNDERSTANDING

SAP-4

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

LEARNING OBJECTIVE

SAP-4.A

Represent a molecule with a Lewis diagram.

ESSENTIAL KNOWLEDGE

SAP-4.A.1

Lewis diagrams can be constructed according to an established set of principles.

SUGGESTED SKILL

Representing Data and Phenomena

3.B

Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 3**

SUGGESTED SKILL

Argumentation

6.C

Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 3**

TOPIC 2.6

Resonance and Formal Charge

Required Course Content

ENDURING UNDERSTANDING

SAP-4

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

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

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.

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.

TOPIC 2.7

VSEPR and Bond Hybridization

SUGGESTED SKILL

Argumentation

6.C

Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 3**

Required Course Content

ENDURING UNDERSTANDING

SAP-4

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

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

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

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°.

continued on next page

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

☒ **AN UNDERSTANDING OF THE DERIVATION AND DEPICTION OF HYBRID ORBITALS WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *The course includes the distinction between sigma and pi bonding, the use of VSEPR to explain the shapes of molecules, and the sp,* sp^2*, and* sp^3 *nomenclature. Additional aspects related to hybridization are both controversial and do not substantially enhance understanding of molecular structure.*

☒ **HYBRIDIZATION INVOLVING D ORBITALS WILL NOT BE ASSESSED ON THE AP EXAM. WHEN AN ATOM HAS MORE THAN FOUR PAIRS OF ELECTRONS SURROUNDING THE CENTRAL ATOM, STUDENTS ARE ONLY RESPONSIBLE FOR THE SHAPE OF THE RESULTING MOLECULE.**

Rationale: *Current evidence suggests that main-group hybridization involving d orbitals does not exist, and there is controversy about the need to teach any hybridization. Until agreement is reached in the chemistry community, we will continue to include only sp,* sp^2*, and* sp^3 *hybridization on the AP Exam.*

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.

☒ **MOLECULAR ORBITAL THEORY IS RECOMMENDED AS A WAY TO PROVIDE DEEPER INSIGHT INTO BONDING. HOWEVER, THE AP EXAM WILL NEITHER EXPLICITLY ASSESS MOLECULAR ORBITAL DIAGRAMS, FILLING OF MOLECULAR ORBITALS, NOR THE DISTINCTION BETWEEN BONDING, NONBONDING, AND ANTIBONDING ORBITALS.**

Rationale: *As currently covered in general chemistry college textbooks, molecular orbital theory is limited to homonuclear molecules in the second period.*

AP CHEMISTRY

UNIT 3

Intermolecular Forces and Properties

18–22%
AP EXAM WEIGHTING

~14–15
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 3

Multiple-choice: ~30 questions
Free-response: 2 questions

- Short-answer
- Short-answer

UNIT 3

18–22% AP EXAM WEIGHTING

~14–15 CLASS PERIODS

Intermolecular Forces and Properties

BIG IDEA 1
Scale, Proportion, and Quantity **SPQ**

- How do interactions between particles influence mixtures?

BIG IDEA 2
Structure and Properties **SAP**

- Why does the smell of perfume only last a short time?
- Why can you swim in water but you cannot walk through a wall?
- How are the properties of gases described?
- How can you determine the structure and concentration of a chemical species in a mixture?

Developing Understanding

Transformations of matter can be observed in ways that are generally categorized as either a chemical or physical change. The shapes of the particles involved and the space between them are key factors in determining the nature of physical changes. The properties of solids, liquids, and gases reflect the relative orderliness of the arrangement of particles in those states, their relative freedom of motion, and the nature and strength of the interactions between them. There is a relationship between the macroscopic properties of solids, liquids, and gases, as well as the structure of the constituent particles of those materials on the molecular and atomic scale. In subsequent units, students will explore chemical transformations of matter.

Building the Science Practices

2.C 2.D 2.E 3.C 4.C 4.D 5.C 5.F

This unit requires students to draw upon claims made in Unit 2 about molecular geometry and polarity to support claims about intermolecular forces between molecules. Further, students will practice illustrating such claims by constructing particle representations of pure solids, liquids, gases, and solutions.

This unit also requires students to build proficiency with mathematical reasoning skills, essential for success in the remainder of the course. Students should be able to explain relationships between variables in an equation (e.g., the ideal gas law) and then estimate the approximate value of one variable within an equation when the value of another variable changes. Students will practice these skills when choosing and implementing experimental procedures, making observations, and/or collecting data to address a question. Students can then determine the accuracy and precision of the data as well as manipulate it with known mathematical equations to support their claims (e.g., concentration of a substance, properties of substances in a mixture).

Preparing for the AP Exam

On the AP Exam (in both the multiple-choice and the free-response section), students must be able to compare the physical properties of substances and relate them to their intermolecular attractive forces. Students often struggle with questions that require them to determine the forces of attraction that are present between molecules. Moreover, it can be challenging for them to determine which forces are most important in explaining the differences in physical properties, such as melting and boiling points and vapor pressures of molecules in the solid and/or liquid state.

Students also confuse the terms intramolecular and intermolecular forces. Another common mistake students make is to simplify their explanations about governing intermolecular forces in a substance by using terms such as “strong” and “weak.” Teachers can ensure that students can identify an actual intermolecular force and explain its strength in relation to other forces at play.

UNIT
3

Intermolecular Forces and Properties

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~14–15 CLASS PERIODS
SAP-5	**3.1 Intermolecular Forces**	**4.D** Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.	
	3.2 Properties of Solids	**4.C** Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.	
SAP-6	**3.3 Solids, Liquids, and Gases**	**3.C** Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).	
SAP-7	**3.4 Ideal Gas Law**	**5.C** Explain the relationship between variables within an equation when one variable changes.	
	3.5 Kinetic Molecular Theory	**4.A** Explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.	
	3.6 Deviation from Ideal Gas Law	**6.E** Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.	
SPQ-3	**3.7 Solutions and Mixtures**	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	3.8 Representations of Solutions	**3.C** Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).	
	3.9 Separation of Solutions and Mixtures Chromatography	**2.C** Identify experimental procedures that are aligned to the question (which may include a sketch of a lab setup).	
	3.10 Solubility	**4.D** Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.	

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Suggested Skill	Class Periods ~14–15 CLASS PERIODS
SAP-8	**3.11** Spectroscopy and the Electromagnetic Spectrum	**4.A** Explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.	
	3.12 Photoelectric Effect	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	3.13 Beer-Lambert Law	**2.E** Identify or describe potential sources of experimental error.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 3. Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	3.1	**Demo with Q&A** Fill a long glass tube halfway with water and then layer ethanol over the top and fill the tube, leaving one inch at the top. Have a student mark the liquid level with a permanent marker and invert the tube (with thumb pressed firmly over the top) several times. A noticeable volume decrease occurs, and students should hypothesize why. Introduce a model showing the interparticle spacing between ethanol molecules and water molecules. The model takes into account the spacing between molecules and why volume is not a conserved quantity (unlike mass). Review hydrogen bonding as a relevant interparticle force for this demonstration.
2	3.3	**Explore Representations** Have students create particle representations for samples of solid, liquid, and gaseous H_2O. Each diagram should contain 10 molecules, and students should show how the placement and motion of the particles varies in each phase.
4	3.7 3.8	**Explore Representations** Begin by telling students that hexane does not mix with water, but ethanol does. Then have them create a particulate representation of each of the mixtures (which illustrate the interactions between the molecules that allow/disallow the solubility).
5	3.9	**Post-Lab Discussion** After investigating three different dyes using chromatography, have students determine which of the three dyes is the most polar based on macroscopic observations and an understanding of the interactions between the dyes and the solvent, or between the dyes and the paper. Then have them discuss their answers (based on evidence) and evaluate the strengths of each other's claims using both the evidence and understanding of intermolecular forces.
7	3.13	**Predict and Confirm** Have students use a Sep-Pak C18 Cartridge (Flinn Scientific AP8917) to separate Grape Kool-Aid into its component red and blue dyes. Then have them compare the separated dyes to reference solutions of common food dyes using a spectrophotometer and measure the percent transmittance at 25 nm intervals across the range of 400 nm–750 nm.

TOPIC 3.1

Intermolecular Forces

Required Course Content

ENDURING UNDERSTANDING

SAP-5

Intermolecular forces can explain the physical properties of a material.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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."

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.

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SUGGESTED SKILL

Model Analysis

4.D

Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 3**
- The Exam > **2017 Chief Reader Report**

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

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.

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.

SAP-5.A.5

In large biomolecules, noncovalent interactions may occur between different molecules or between different regions of the same large biomolecule.

TOPIC 3.2

Properties of Solids

Required Course Content

ENDURING UNDERSTANDING

SAP-5

Intermolecular forces can explain the physical properties of a material.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

SAP-5.B.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.

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.

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SUGGESTED SKILL

Model Analysis

4.C

Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 6: What's in That Bottle?**

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

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.

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.

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.

TOPIC 3.3

Solids, Liquids, and Gases

Required Course Content

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

SAP-6.A

Represent the differences between solid, liquid, and gas phases using a particulate-level model.

ESSENTIAL KNOWLEDGE

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.

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.

continued on next page

SUGGESTED SKILL

Representing Data and Phenomena

3.C

Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).

AVAILABLE RESOURCES

- The Exam > **2017 Chief Reader Report**

LEARNING OBJECTIVE

SAP-6.A

Represent the differences between solid, liquid, and gas phases using a particulate-level model.

ESSENTIAL KNOWLEDGE

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.

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.

☒ **UNDERSTANDING/INTERPRETING PHASE DIAGRAMS WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Phase diagrams of pure substances are considered prior knowledge.*

TOPIC 3.4

Ideal Gas Law

Required Course Content

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

SAP-7.A

Explain the relationship between the macroscopic properties of a sample of gas or mixture of gases using the ideal gas law.

ESSENTIAL KNOWLEDGE

SAP-7.A.1

The macroscopic properties of ideal gases are related through the ideal gas law:

EQN: $PV = nRT$.

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: $P_A = P_{total} \times X_A$,

where X_A = moles A/total moles;

EQN: $P_{total} = P_A + P_B + P_C + \ldots$

SAP-7.A.3

Graphical representations of the relationships between P, V, T, and n are useful to describe gas behavior.

SUGGESTED SKILL

Mathematical Routines

5.C

Explain the relationship between variables within an equation when one variable changes.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**
- The Exam > **2017 Chief Reader Report**

SUGGESTED SKILL

Model Analysis

4.A

Explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**
- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

TOPIC 3.5

Kinetic Molecular Theory

Required Course Content

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

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.

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.

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: $KE = \frac{1}{2} mv^2$.

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.

SAP-7.B.4

The Maxwell-Boltzmann distribution provides a graphical representation of the energies/velocities of particles at a given temperature.

TOPIC 3.6

Deviation from Ideal Gas Law

SUGGESTED SKILL

Argumentation

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

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

SAP-7.C

Explain the relationship among non-ideal behaviors of gases, interparticle forces, and/or volumes.

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.

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 7: Using the Principle That Each Substance Has Unique Properties to Purify a Mixture: An Experiment in Applying Green Chemistry in Purification**

TOPIC 3.7

Solutions and Mixtures

Required Course Content

ENDURING UNDERSTANDING

SPQ-3

Interactions between intermolecular forces influence the solubility and separation of mixtures.

LEARNING OBJECTIVE

SPQ-3.A

Calculate the number of solute particles, volume, or molarity of solutions.

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.

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: $M = n_{solute}/L_{solution}$

TOPIC 3.8

Representations of Solutions

SUGGESTED SKILL

Representing Data and Phenomena

3.C

Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).

Required Course Content

ENDURING UNDERSTANDING

SPQ-3

Interactions between intermolecular forces influence the solubility and separation of mixtures.

LEARNING OBJECTIVE

SPQ-3.B

Using particulate models for mixtures:

a. Represent interactions between components.

b. Represent concentrations of components.

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.

☒ **COLLIGATIVE PROPERTIES WILL NOT BE ASSESSED ON THE AP EXAM.**

☒ **CALCULATIONS OF MOLALITY, PERCENT BY MASS, AND PERCENT BY VOLUME WILL NOT BE ASSESSED ON THE AP EXAM.**

SUGGESTED SKILL

Question and Method

2.C

Identify experimental procedures that are aligned to the question (which may include a sketch of a lab setup).

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 5: Sticky Question: How Do You Separate Molecules That Are Attracted to One Another?**

TOPIC 3.9

Separation of Solutions and Mixtures Chromatography

Required Course Content

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.

TOPIC 3.10

Solubility

SUGGESTED SKILL

Model Analysis

4.D

Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.

Required Course Content

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.

SUGGESTED SKILL

Model Analysis

4.A

Explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 1: What is the Relationship Between the Concentration of a Solution and the Amount of Transmitted Light Through the Solution?**

TOPIC 3.11

Spectroscopy and the Electromagnetic Spectrum

Required Course Content

ENDURING UNDERSTANDING

SAP-8

Spectroscopy can determine the structure and concentration in a mixture of a chemical species.

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.

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.

TOPIC 3.12

Photoelectric Effect

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

Required Course Content

ENDURING UNDERSTANDING

SAP-8

Spectroscopy can determine the structure and concentration in a mixture of a chemical species.

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.

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.

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 ($E = h\nu$).

SUGGESTED SKILL

Question and Method

2.E

Identify or describe potential sources of experimental error.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 3.13

Beer-Lambert Law

Required Course Content

ENDURING UNDERSTANDING

SAP-8

Spectroscopy can determine the structure and concentration in a mixture of a chemical species.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

SAP-8.C.1

The Beer-Lambert law relates the absorption of light by a solution to three variables according to the equation:

EQN: $A = \mathcal{E}bc$.

The molar absorptivity $\mathcal{E}$ 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.

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.

AP CHEMISTRY

UNIT 4

Chemical Reactions

7–9%
AP EXAM WEIGHTING

~14–15
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 4

Multiple-choice: ~20 questions
Free-response: 1 question

- Long-answer

UNIT 4

7–9% AP EXAM WEIGHTING

~14–15 CLASS PERIODS

Chemical Reactions

BIG IDEA 1
Scale, Proportion, and Quantity **SPQ**
- What makes fireworks explode?

BIG IDEA 3
Transformations **TRA**
- Why is the mass of a raw egg different than a boiled egg?
- What are the processes related to changes in a substance?

Developing Understanding

This unit explores chemical transformations of matter by building on the physical transformations studied in Unit 3. Chemical changes involve the making and breaking of chemical bonds. Many properties of a chemical system can be understood using the concepts of varying strengths of chemical bonds and weaker intermolecular interactions. When chemical changes occur, the new substances formed have properties that are distinguishable from the initial substance or substances. Chemical reactions are the primary means by which transformations in matter occur. Chemical equations are a representation of the rearrangement of atoms that occur during a chemical reaction. In subsequent units, students will explore rates at which chemical changes occur.

Building the Science Practices

1.B 2.B 5.C 5.E 6.B

In Unit 3, students constructed particulate-level representations of compounds and molecules and explained the forces that come into play when particles interact. In Unit 4, students will describe and construct equations of chemical systems and learn to balance those equations. Students should be able to identify and effectively represent types of reactions (e.g., acid-base, redox, precipitation) and then use that knowledge to make hypotheses or predictions about the outcome of a reaction. Additionally, students should be able to support their claims about the identity and amount of product yield through evidence gained with both experimentation and the principles of stoichiometry. Further, students should be able to determine the output of a reaction when the number of moles of reactants change or are in limited/excess supply. This practice of effectively representing balanced chemical equations and using stoichiometry to calculate outcomes of such reactions is critical to student success in the remainder of the course.

Preparing for the AP Exam

On the AP Exam, students must be able to demonstrate proficiency in writing and balancing chemical equations (molecular, complete, net ionic) and calculating quantities in multiple contexts using more than just 1:1 stoichiometric ratios. Students often struggle with questions that require them to justify their identification of a particular type of reaction using an equation. They also struggle with determining the limiting reactant using stoichiometry. For example, with stoichiometric calculations, students often make the mistake of comparing mass to mass instead of mole to mole when determining the limiting reactant. Teacher can ensure that students practice writing balanced equations (for net ionic and molecular) and that they develop a strong understanding of the mole concept and gain proficiency with dimensional analysis. This will help them correctly calculate required quantities using stoichiometric ratios.

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~14–15 CLASS PERIODS
TRA-1	**4.1 Introduction for Reactions**	**2.B** Formulate a hypothesis or predict the results of an experiment.	
	4.2 Net Ionic Equations	**5.E** Determine a balanced chemical equation for a given chemical phenomena.	
	4.3 Representations of Reactions	**3.B** Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).	
	4.4 Physical and Chemical Changes	**6.B** Support a claim with evidence from experimental data.	
SPQ-4	**4.5 Stoichiometry**	**5.C** Explain the relationship between variables within an equation when one variable changes.	
	4.6 Introduction to Titration	**3.A** Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.	
TRA-2	**4.7 Types of Chemical Reactions**	**1.B** Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.	
	4.8 Introduction to Acid-Base Reactions	**1.B** Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.	
	4.9 Oxidation-Reduction (Redox) Reactions	**5.E** Determine a balanced chemical equation for a given chemical phenomena.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 4. Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	4.2 4.3	**Explore Representations** Have students work through an online simulation of particulate-level representations of various single-displacement reactions. Then have them translate these particle-level views into net ionic equations.
2	4.5	**Simulations** Have students view a simulated reaction pertaining to a limiting reagent problem. Each iteration of the simulation provides students with different unknown concentrations of the reactants from which students calculate the amount of product that is dissolved. Then have them check their answers upon completion of the simulation.
3	4.6	**Think-Pair-Share** Ask students to connect four different particulate representations with a strong acid-strong base titration curve between HCl + NaOH. The representations depict the acid before base has been added, the half equivalence point of the titration, the equivalence point of the titration, and some point beyond the equivalence point (excess base). Have students defend their choices with a partner.
4	4.7	**Critique Reasoning** After a review of different types of chemical reactions (acid-base, redox, precipitation), give students a series of 10 reactions (both the equation and a short demo of the reaction taking place). Have them identify what type of reaction is taking place and justify that claim with evidence. Then have them pair up and evaluate the strength of each other's claims.
5	4.9	**Simulations** After viewing a simulation on metal/metal ion reactions, provide students with several 1 molar solutions and a piece of aluminum and ask them to select a solution that would react to coat the Al. Students who select incorrect solutions should go back and revisit the simulation.

SUGGESTED SKILL

Question and Method

2.B

Formulate a hypothesis or predict the results of an experiment.

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 1**

TOPIC 4.1

Introduction for Reactions

Required Course Content

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

TRA-1.A

Identify evidence of chemical and physical changes in matter.

ESSENTIAL KNOWLEDGE

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.

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.

TOPIC 4.2

Net Ionic Equations

Required Course Content

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

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.

ESSENTIAL KNOWLEDGE

TRA-1.B.1

All physical and chemical processes can be represented symbolically by balanced equations.

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.

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.

SUGGESTED SKILL

Mathematical Routines

5.E

Determine a balanced chemical equation for a given chemical phenomena.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 8: How Can We Determine the Actual Percentage of H2O2 in a Drugstore Bottle of Hydrogen Peroxide?**

SUGGESTED SKILL

Representing Data and Phenomena

3.B

Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 1**

TOPIC 4.3

Representations of Reactions

Required Course Content

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

TRA-1.C

Represent a given chemical reaction or physical process with a consistent particulate model.

ESSENTIAL KNOWLEDGE

TRA-1.C.1

Balanced chemical equations in their various forms can be translated into symbolic particulate representations.

TOPIC 4.4

Physical and Chemical Changes

SUGGESTED SKILL

Argumentation

6.B

Support a claim with evidence from experimental data.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 9: Can the Individual Components of Quick Ache Relief Be Used to Resolve Consumer Complaint?**

Required Course Content

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. **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.

SUGGESTED SKILL

Mathematical Routines

5.C

Explain the relationship between variables within an equation when one variable changes.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 7: Using the Principle That Each Substance Has Unique Properties to Purify a Mixture: An Experiment in Applying Green Chemistry to Purification**

TOPIC 4.5
Stoichiometry

Required Course Content

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

SPQ-4.A

Explain changes in the amounts of reactants and products based on the balanced reaction equation for a chemical process.

ESSENTIAL KNOWLEDGE

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.

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.

SPQ-4.A.3

Stoichiometric calculations can be combined with the ideal gas law and calculations involving molarity to quantitatively study gases and solutions.

TOPIC 4.6

Introduction to Titration

Required Course Content

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

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.

ESSENTIAL KNOWLEDGE

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.

SUGGESTED SKILL

Representing Data and Phenomena

3.A

Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 4: How Much Acid Is in Fruit Juice and Soft Drinks?**

SUGGESTED SKILL

Models and Representations

1.B

Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.

TOPIC 4.7

Types of Chemical Reactions

Required Course Content

ENDURING UNDERSTANDING

TRA-2

A substance can change into another substance through different processes, and the change itself can be classified by the sort of processes that produced it.

LEARNING OBJECTIVE

TRA-2.A

Identify a reaction as acid-base, oxidation-reduction, or precipitation.

ESSENTIAL KNOWLEDGE

TRA-2.A.1

Acid-base reactions involve transfer of one or more protons between chemical species.

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.

TRA-2.A.3

In a redox reaction, electrons are transferred from the species that is oxidized to the species that is reduced.

X THE MEANING OF THE TERMS "REDUCING AGENT" AND "OXIDIZING AGENT" WILL NOT BE ASSESSED ON THE AP EXAM.

Rationale: *Understanding this terminology is not necessary for reasoning about redox chemistry.*

continued on next page

LEARNING OBJECTIVE

TRA-2.A

Identify a reaction as acid-base, oxidation-reduction, or precipitation.

ESSENTIAL KNOWLEDGE

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.

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.

☒ ROTE MEMORIZATION OF “SOLUBILITY RULES” OTHER THAN THOSE IMPLIED IN TRA-2.A.5 WILL NOT BE ASSESSED ON THE AP EXAM.

SUGGESTED SKILL

Models and Representations

1.B

Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.

AVAILABLE RESOURCES

- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 2**

TOPIC 4.8

Introduction to Acid-Base Reactions

Required Course Content

ENDURING UNDERSTANDING

TRA-2

A substance can change into another substance through different processes, and the change itself can be classified by the sort of processes that produced it.

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.

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.

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.

☒ **LEWIS ACID-BASE CONCEPTS WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Lewis acid-base concepts are important ideas for organic chemistry. However, as the emphasis in AP Chemistry is on reactions in aqueous solution, these concepts will not be examined.*

TOPIC 4.9

Oxidation-Reduction (Redox) Reactions

SUGGESTED SKILL

Mathematical Routines

5.E

Determine a balanced chemical equation for a given chemical phenomena.

Required Course Content

ENDURING UNDERSTANDING

TRA-2

A substance can change into another substance through different processes, and the change itself can be classified by the sort of processes that produced it.

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.

AP CHEMISTRY

UNIT 5

Kinetics

7–9%
AP EXAM WEIGHTING

~13–14
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 5

Multiple-choice: ~25 questions
Free-response: 2 questions

- Short-answer
- Long-answer

UNIT 5

7–9% AP EXAM WEIGHTING

~13–14 CLASS PERIODS

Kinetics

BIG IDEA 3

Transformations **TRA**

- Why are some reactions faster than other reactions?
- How long will a marble statue last?
- How can a sports drink cure a headache?

BIG IDEA 4

Energy **ENE**

- Why does bread rise?

Developing Understanding

Unit 4 focused on chemical changes; in Unit 5 students will develop an understanding of the rates at which chemical changes occur and the factors that influence the rates. Those factors include the concentration of reactants, temperature, catalysts, and other environmental factors. Chemical changes are represented by chemical reactions, and the rates of chemical reactions are determined by the details of the molecular collisions. Rates of change in chemical reactions are observable and measurable. When measuring rates of change, students are measuring the concentration of reactant or product species as a function of time. These chemical processes may be observed in a variety of ways and often involve changes in energy as well. In subsequent units, students will describe the role of energy in changes in matter.

Building the Science Practices

1.B 5.B 5.C 5.E 6.E

In prior units, students developed their ability to describe symbolic and quantitative information from representations (e.g., Lewis structures, chemical reactions) that illustrate both the particulate and macroscopic level of a chemical phenomenon. In Unit 5, students will build on these explanations and representations by constructing and describing rate laws consistent with experimental evidence. To that end, students will collect data by spectrophotometry and choose an appropriate mathematical routine to determine how concentration varies with time during the course of a reaction. In addition, students will examine proposed reaction mechanisms to determine if there is a match between observed experimental data and constructed rate law expressions. Students will learn to identify any intermediates or catalysts that are included in the reaction mechanism, as well as the rate-determining step, and be able to justify their claims. To do so, students must learn to construct and analyze energy profiles for chemical reactions and identify how such profiles may change with the addition of a catalyst.

Preparing for the AP Exam

On the AP Exam, students must be able to navigate between experimental data (tabular or graphed), a given or constructed rate law, and a proposed mechanism. Students generally struggle with reading a graph of reactant concentration versus time and drawing appropriate conclusions (i.e., order and rate constant) from the graphed data. Specifically, students confuse the units of the graphs with the units represented in the chemical equation. Teachers can ensure that students have multiple opportunities to graph concentration versus time or concentration versus rate data (using appropriate increments and units for the axes). Once students learn how to graph this data, teacher can help them analyze the graphs to determine the order of a reaction.

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~13–14 CLASS PERIODS
TRA-3	**5.1 Reaction Rates**	**6.E** Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.	
	5.2 Introduction to Rate Law	**5.C** Explain the relationship between variables within an equation when one variable changes.	
	5.3 Concentration Changes Over Time	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
TRA-4	**5.4 Elementary Reactions**	**5.E** Determine a balanced chemical equation for a given chemical phenomena.	
	5.5 Collision Model	**6.E** Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.	
	5.6 Reaction Energy Profile	**3.B** Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).	
TRA-5	**5.7 Introduction to Reaction Mechanisms**	**1.B** Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.	
	5.8 Reaction Mechanism and Rate Law	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	5.9 Steady-State Approximation	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	5.10 Multistep Reaction Energy Profile	**3.B** Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).	
ENE-1	**5.11 Catalysis**	**6.E** Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 5. Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	5.1	**Post-Lab Discussion** As an introduction to kinetics, have students form small groups to design an experiment to establish a relationship between the rate and a specific reaction parameter of Alka-Seltzer tablets in water. Have them select varying temperature, concentration, mass, or surface area and decide which data to collect. Groups use whiteboards to present their data and major findings to the rest of the class.
2	5.2	**Post-Lab Discussion** Using a spectrophotometer, have students measure the absorbance of a solution of green food coloring after bleach has been added. Have them use Excel to prepare different graphs of the data, such as absorbance vs. time, and 1/(absorbance) vs. time. Students should use a linear regression analysis to determine the most linear fit, the order of the reaction, and the effect on the value of k when the concentration of bleach is increased. Have student groups share and compare their results.
3	5.3	**Critique Reasoning** Using a balance and a stopwatch, have students determine the rate order of a burning birthday candle by preparing graphs in Excel, and use a linear regression analysis to determine the most linear fit and the value of the rate constant, k. Have students justify why the rate of mass disappearance of the candle does not change as the candle burns down. Then have them compare their results with other groups to see if their results are consistent.
4	5.7 5.8	**Critique Reasoning** Working in small groups, have students evaluate the appropriateness of reaction mechanisms for a given reaction for which the rate law is established. Have groups share their conclusions with the rest of the class and then discuss why certain choices must be eliminated and why there might be more than one possible mechanism that is valid. Have classmates provide feedback to the groups on the validity of their conclusions.
5	5.10	**Manipulatives** Give students a blank multistep reaction energy profile with a series of labels on the side. Have them work with a partner to correctly place the labels next to the blanks indicated on the profile and then share/evaluate their diagrams with another pair of students.

SUGGESTED SKILL

Argumentation

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 10: How Long Will That Marble Statue Last?**
- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

TOPIC 5.1

Reaction Rates

Required Course Content

ENDURING UNDERSTANDING

TRA-3

Some reactions happen quickly, while others happen more slowly and depend on reactant concentrations and temperature.

LEARNING OBJECTIVE

TRA-3.A

Explain the relationship between the rate of a chemical reaction and experimental parameters.

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.

TRA-3.A.2

The rates of change of reactant and product concentrations are determined by the stoichiometry in the balanced chemical equation.

TRA-3.A.3

The rate of a reaction is influenced by reactant concentrations, temperature, surface area, catalysts, and other environmental factors.

TOPIC 5.2
Introduction to Rate Law

SUGGESTED SKILL

Mathematical Routines

5.C

Explain the relationship between variables within an equation when one variable changes.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 11: What Is the Rate Law of the Fading of Crystal Violet Using Beer's Law?**
- The Exam > **2017 Chief Reader Report**

Required Course Content

ENDURING UNDERSTANDING

TRA-3

Some reactions happen quickly, while others happen more slowly and depend on reactant concentrations and temperature.

LEARNING OBJECTIVE

TRA-3.B

Represent experimental data with a consistent rate law expression.

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.

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.

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.

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.

TRA-3.B.5

Comparing initial rates of a reaction is a method to determine the order with respect to each reactant.

TOPIC 5.3

Concentration Changes Over Time

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 11: What Is the Rate Law of the Fading of Crystal Violet Using Beer's Law?**
- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

Required Course Content

ENDURING UNDERSTANDING

TRA-3

Some reactions happen quickly, while others happen more slowly and depend on reactant concentrations and temperature.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

TRA-3.C.1

The order of a reaction can be inferred from a graph of concentration of reactant versus time.

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.

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.

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:

$$\text{EQN: } [\mathrm{A}]_t - [\mathrm{A}]_0 = -kt$$

First order:

$$\text{EQN: } \ln[\mathrm{A}]_t - \ln[\mathrm{A}]_0 = -kt$$

Second order:

$$\text{EQN: } 1/[\mathrm{A}]_t - 1/[\mathrm{A}]_0 = kt$$

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LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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: $t_{1/2} = 0.693/k$.

TRA-3.C.6

Radioactive decay processes provide an important illustration of first order kinetics.

SUGGESTED SKILL

Mathematical Routines

5.E

Determine a balanced chemical equation for a given chemical phenomena.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

TOPIC 5.4

Elementary Reactions

Required Course Content

ENDURING UNDERSTANDING

TRA-4

There is a relationship between the speed of a reaction and the collision frequency of particle collisions.

LEARNING OBJECTIVE

TRA-4.A

Represent an elementary reaction as a rate law expression using stoichiometry.

ESSENTIAL KNOWLEDGE

TRA-4.A.1

The rate law of an elementary reaction can be inferred from the stoichiometry of the molecules participating in a collision.

TRA-4.A.2

Elementary reactions involving the simultaneous collision of three or more particles are rare.

TOPIC 5.5

Collision Model

SUGGESTED SKILL

Argumentation

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

Required Course Content

ENDURING UNDERSTANDING

TRA-4

There is a relationship between the speed of a reaction and the collision frequency of particle collisions.

LEARNING OBJECTIVE

TRA-4.B

Explain the relationship between the rate of an elementary reaction and the frequency, energy, and orientation of molecular collisions.

ESSENTIAL KNOWLEDGE

TRA-4.B.1

For an elementary reaction to successfully produce products, reactants must successfully collide to initiate bond-breaking and bond-making events.

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.

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.

SUGGESTED SKILL

Representing Data and Phenomena

3.B

Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).

AVAILABLE RESOURCES

- The Exam > **2017 Chief Reader Report**

TOPIC 5.6

Reaction Energy Profile

Required Course Content

ENDURING UNDERSTANDING

TRA-4

There is a relationship between the speed of a reaction and the collision frequency of particle collisions.

LEARNING OBJECTIVE

TRA-4.C

Represent the activation energy and overall energy change in an elementary reaction using a reaction energy profile.

ESSENTIAL KNOWLEDGE

TRA-4.C.1

Elementary reactions typically involve the breaking of some bonds and the forming of new ones.

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.

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.

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.

☒ **CALCULATIONS INVOLVING THE ARRHENIUS EQUATION WILL NOT BE ASSESSED ON THE AP EXAM.**

TOPIC 5.7

Introduction to Reaction Mechanisms

Required Course Content

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.A

Identify the components of a reaction mechanism.

ESSENTIAL KNOWLEDGE

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.

TRA-5.A.2

The elementary steps when combined should align with the overall balanced equation of a chemical reaction.

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.

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.

☒ **COLLECTION OF DATA PERTAINING TO DETECTION OF A REACTION INTERMEDIATE WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Designing an experiment to identify reaction intermediates often requires knowledge that is beyond the scope of a general chemistry course.*

SUGGESTED SKILL

Models and Representations

1.B

Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

TOPIC 5.8

Reaction Mechanism and Rate Law

Required Course Content

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.B

Identify the rate law for a reaction from a mechanism in which the first step is rate limiting.

ESSENTIAL KNOWLEDGE

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).

☒ **COLLECTION OF DATA PERTAINING TO DETECTION OF A REACTION INTERMEDIATE WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Designing an experiment to identify reaction intermediates often requires knowledge that is beyond the scope of a general chemistry course.*

TOPIC 5.9

Steady-State Approximation

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

Required Course Content

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.C

Identify the rate law for a reaction from a mechanism in which the first step is not rate limiting.

ESSENTIAL KNOWLEDGE

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.

SUGGESTED SKILL

Representing Data and Phenomena

3.B

Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

TOPIC 5.10

Multistep Reaction Energy Profile

Required Course Content

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.

TOPIC 5.11

Catalysis

Required Course Content

ENDURING UNDERSTANDING

ENE-1

The speed at which a reaction occurs can be influenced by a catalyst.

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.

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.

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.

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.

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SUGGESTED SKILL

Argumentation

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
ENE-1.A Explain the relationship between the effect of a catalyst on a reaction and changes in the reaction mechanism.	**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).

AP CHEMISTRY

UNIT 6

Thermodynamics

7–9%
AP EXAM WEIGHTING

~10–11
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 6

Multiple-choice: ~20 questions
Free-response: 2 questions

- Short-answer
- Short-answer

UNIT
6

7–9% AP EXAM WEIGHTING

~10–11 CLASS PERIODS

Thermodynamics

BIG IDEA 4
Energy **ENE**

- Why is energy released when water becomes an ice cube?
- How are chemical transformations that require bonds to break and form influenced by energy?

Developing Understanding

The laws of thermodynamics describe the essential role of energy and explain and predict the direction of changes in matter. The availability or disposition of energy plays a role in virtually all observed chemical processes. Thermodynamics provides tools for understanding this key role, particularly the conservation of energy, including energy transfer in the forms of heat and work. Chemical bonding is central to chemistry. A key concept to know is that the breaking of a chemical bond inherently requires an energy input, and because bond formation is the reverse process, it will release energy. In subsequent units, the application of thermodynamics will determine the favorability of a reaction occurring.

Building the Science Practices

5.F **6.D** **6.E**

The ability to link atomic- and particulate-level phenomena and models to macroscopic phenomena is central to the study of chemistry. In previous units, students used representations, equations, and reasoning to demonstrate this ability. In Unit 6, students will develop justifications for claims made about the direction of thermal energy transfer of a system in relation to its surroundings when a temperature change, physical change, or a chemical reaction occurs. Students will construct representations of energy using appropriate diagrams with arrows showing the direction of energy transfer between the system and the surroundings. They will continue to develop their explanations of chemical phenomena by explaining how the change in energy of a system is balanced by transfer of energy by either heat or work into or out of the system.

Preparing for the AP Exam

On the AP Exam, students must be able to translate between a balanced chemical reaction and a calculation involving the energies of bonds broken and bonds formed within the reaction. In addition, students will be required to analyze calorimetry data and apply mathematical routines to calculate or estimate the heat transferred and the overall enthalpy of a reaction. In a question that asks students to apply mathematical routines to estimate or calculate the overall enthalpy of a reaction, students often struggle to determine the number of bonds that were broken and made in the reaction. Teachers can ensure that students are able to identify the bonds broken and formed in the reaction and use the enthalpies for such to determine the overall enthalpy for the reaction, in addition to their ability to represent a chemical reaction with its associated equation.

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~10–11 CLASS PERIODS
ENE-2	**6.1 Endothermic and Exothermic Processes**	**6.D** Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	
	6.2 Energy Diagrams	**3.A** Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.	
	6.3 Heat Transfer and Thermal Equilibrium	**6.E** Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.	
	6.4 Heat Capacity and Calorimetry	**2.D** Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.	
	6.5 Energy of Phase Changes	**1.B** Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.	
	6.6 Introduction to Enthalpy of Reaction	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
ENE-3	**6.7 Bond Enthalpies**	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	6.8 Enthalpy of Formation	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	6.9 Hess's Law	**5.A** Identify quantities needed to solve a problem from given information (e.g., text, mathematical expressions, graphs, or tables).	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 6.
Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	**6.1** **6.2**	**Think-Pair-Share** Have student pairs generate a list of exothermic and endothermic processes that occur in their everyday life. Have them share their lists with other pairs to determine if they have correctly identified these common processes in terms of endo- or exothermicity.
2	**6.3**	**Demo with Q&A** After working a few practice problems in groups with the $q = mC\Delta T$ equation, demonstrate that heating 40 g of copper pellets to $80°$C and placing them into 40 g of $20°$C water does not result in $50°$C as a final temperature. Have students reason why and then record the final temperature of the copper/water mixture. Then have them calculate the specific heat capacity of copper and compare it to published values. As a class discussion, account for deviations from the expected results.
3	**6.4**	**Process Oriented Guided Inquiry Learning (POGIL)** Have students wet one finger with water and keep one finger dry then wave them in the air to see which feels cooler. Have them respond to a series of guided questions about the energy transfers involved in the evaporation process. Next, two beakers are heated side by side on a hot plate. Heating a beaker with 100 g of water on the same hot plate alongside a beaker with 100 g of 1-propanol results in very different changes in temperature. Through guided inquiry, students derive the concept of specific heat. As a class, compare whether the two liquids have been treated “fairly,” and the concept of molar heat capacity is established and compared to specific heat capacity.
4	**6.7** **6.8**	**Think-Pair-Share** Have pairs of students examine tables of average bond enthalpy and establish patterns with regard to bond order, atomic radius, and bond length. Similar patterns are examined for the standard enthalpies of formation. Have student pairs work through several practice problems using bond energies and enthalpies of formation to determine the enthalpy of a chemical reaction and compare their calculations.
5	**6.9**	**Post-Lab Discussion** Have students apply Hess’s law by reacting magnesium metal and magnesium oxide with hydrochloric acid to determine the enthalpy change of the following reaction: $Mg + O_2 \rightarrow MgO$. Then have them evaluate their results and discuss sources of error.

SUGGESTED SKILL

Argumentation

6.D

Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 6.1

Endothermic and Exothermic Processes

Required Course Content

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.A

Explain the relationship between experimental observations and energy changes associated with a chemical or physical transformation.

ESSENTIAL KNOWLEDGE

ENE-2.A.1

Temperature changes in a system indicate energy changes.

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.

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.

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.

TOPIC 6.2

Energy Diagrams

SUGGESTED SKILL

Representing Data and Phenomena

3.A

Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.

Required Course Content

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.B

Represent a chemical or physical transformation with an energy diagram.

ESSENTIAL KNOWLEDGE

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.

SUGGESTED SKILL

Argumentation

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

TOPIC 6.3

Heat Transfer and Thermal Equilibrium

Required Course Content

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

The particles in a warmer body have a greater average kinetic energy than those in a cooler body.

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."

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.

TOPIC 6.4

Heat Capacity and Calorimetry

Required Course Content

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.

ENE-2.D.2

The first law of thermodynamics states that energy is conserved in chemical and physical processes.

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.

ENE-2.D.4

Heating a system increases the energy of the system, while cooling a system decreases the energy of the system.

ENE-2.D.5

The specific heat capacity of a substance and the molar heat capacity are both used in energy calculations.

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SUGGESTED SKILL

Question and Method

2.D

Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 12: The Hand Warmer Challenge: Where Does the Heat Come From?**

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.6

Chemical systems change their energy through three main processes: heating/cooling, phase transitions, and chemical reactions.

TOPIC 6.5

Energy of Phase Changes

Required Course Content

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.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.

ESSENTIAL KNOWLEDGE

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.

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.

SUGGESTED SKILL

Models and Representations

1.B

Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 12: The Hand Warmer Challenge: Where Does the Heat Come From?**

SUGGESTED SKILL

Model Analysis

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 12: The Hand Warmer Challenge: Where Does the Heat Come From?**

TOPIC 6.6

Introduction to Enthalpy of Reaction

Required Course Content

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.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.

ESSENTIAL KNOWLEDGE

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.

☒ **THE TECHNICAL DISTINCTIONS BETWEEN ENTHALPY AND INTERNAL ENERGY WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale*: These distinctions are beyond the scope of the AP Chemistry course. Most reactions studied at the AP level are carried out at constant pressure. Under these conditions the enthalpy change of the process is equal to the heat (and by extension, the energy) of reaction. For example, in the AP Chemistry course the terms "bond energy" and "bond enthalpy" are often used interchangeably.*

TOPIC 6.7

Bond Enthalpies

Required Course Content

ENDURING UNDERSTANDING

ENE-3

The energy exchanged in a chemical transformation is required to break and form bonds.

LEARNING OBJECTIVE

ENE-3.A

Calculate the enthalpy change of a reaction based on the average bond energies of bonds broken and formed in the reaction.

ESSENTIAL KNOWLEDGE

ENE-3.A.1

During a chemical reaction, bonds are broken and/or formed, and these events change the potential energy of the system.

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.

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 6.8

Enthalpy of Formation

Required Course Content

ENDURING UNDERSTANDING

ENE-3

The energy exchanged in a chemical transformation is required to break and form bonds.

LEARNING OBJECTIVE

ENE-3.B

Calculate the enthalpy change for a chemical or physical process based on the standard enthalpies of formation.

ESSENTIAL KNOWLEDGE

ENE-3.B.1

Tables of standard enthalpies of formation can be used to calculate the standard enthalpies of reactions.

EQN: $\Delta H^\circ_{\text{reaction}} = \Sigma \Delta H_f^\circ{}_{\text{products}} - \Sigma \Delta H_f^\circ{}_{\text{reactants}}$

TOPIC 6.9

Hess's Law

Required Course Content

ENDURING UNDERSTANDING

ENE-3

The energy exchanged in a chemical transformation is required to break and form bonds.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
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.
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.

SUGGESTED SKILL

Mathematical Routines

5.A

Identify quantities needed to solve a problem from given information (e.g., text, mathematical expressions, graphs, or tables).

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

AP CHEMISTRY

UNIT 7

Equilibrium

7–9%
AP EXAM WEIGHTING

~14–16
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 7

Multiple-choice: ~30 questions
Free-response: 2 questions

- Short-answer
- Long-answer

UNIT
7

7–9% AP EXAM WEIGHTING

~14–16 CLASS PERIODS

Equilibrium

BIG IDEA 1
Scale, Proportion, and Quantity **SPQ**
- Why is a waterfall considered a spontaneous reaction?

BIG IDEA 3
Transformation **TRA**
- How can reactions occur in more than one direction?
- How is caffeine removed from coffee?
- Why is food stored in a refrigerator?

Developing Understanding

Chemical equilibrium is a dynamic state in which opposing processes occur at the same rate. In this unit, students learn that any bond or intermolecular attraction that can be formed can be broken. These two processes are in a dynamic competition, sensitive to initial conditions and external perturbations. A change in conditions, such as addition of a chemical species, change in temperature, or change in volume, can cause the rate of the forward and reverse reactions to fall out of balance. Le Châtelier's principle provides a means to reason qualitatively about the direction of the shift in an equilibrium system resulting from various possible stresses. The expression for the equilibrium constant, K, is a mathematical expression that describes the equilibrium state associated with a chemical change. An analogous expression for the reaction quotient, Q, describes a chemical reaction at any point, enabling a comparison to the equilibrium state. Subsequent units will explore equilibrium constants that arise from acid-base chemistry.

Building the Science Practices

2.D **2.F** **3.A** **3.C** **4.D** **6.D** **6.F**

Building on practices from earlier units where students translated between representations of chemical systems, they will now construct equilibrium expressions from reaction equations. Students should also illustrate the dynamic nature of the chemical reaction through particulate-level representations, portraying both the forward and reverse rates of the reaction equations. They will construct and describe graphs that represent a chemical system in equilibrium and connect them to their particulate-level representations and equilibrium expressions. In conjunction with their constructed equilibrium expressions, students will practice using experimental data to calculate the reaction quotient (Q) and equilibrium constant (K) for a reaction. Using Le Châtelier's principle, they will also support claims made about the dominant direction of a reaction once stresses like changes in concentration, pressure, volume, or temperature are introduced.

Preparing for the AP Exam

On the AP Exam, students must be able to connect what is happening at the molecular level to a model for a system at equilibrium. For example, when students are asked to connect the value of the equilibrium constant (K) from the equilibrium expression to the dominant direction of the reaction, they struggle to connect the value of a large K to a reaction proceeding essentially to completion. This lack of connection leads students to use ineffective mathematical routines and then incorrectly calculate the concentration of the product in solution. To help students avoid this type of misunderstanding, teachers can ensure that students connect the value of the equilibrium constant to the experimental data or observations provided. Additionally, teachers can help students visualize the effects of a large or small equilibrium constant on the concentrations of all species in equilibrium.

UNIT 7

Equilibrium

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~14–16 CLASS PERIODS
TRA-6	**7.1 Introduction to Equilibrium**	**6.D** Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	
	7.2 Direction of Reversible Reactions	**4.D** Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.	
TRA-7	**7.3 Reaction Quotient and Equilibrium Constant**	**3.A** Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.	
	7.4 Calculating the Equilibrium Constant	**5.C** Explain the relationship between variables within an equation when one variable changes.	
	7.5 Magnitude of the Equilibrium Constant	**6.D** Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	
	7.6 Properties of the Equilibrium Constant	**5.A** Identify quantities needed to solve a problem from given information (e.g., text, mathematical expressions, graphs, or tables).	
	7.7 Calculating Equilibrium Concentrations	**3.A** Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.	
	7.8 Representations of Equilibrium	**3.C** Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).	
TRA-8	**7.9 Introduction to Le Châtelier's Principle**	**6.F** Explain the connection between experimental results and chemical concepts, processes, or theories.	
	7.10 Reaction Quotient and Le Châtelier's Principle	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Suggested Skill	Class Periods ~14–16 CLASS PERIODS
SPQ-5	**7.11 Introduction to Solubility Equilibria**	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	7.12 Common-Ion Effect	**2.F** Explain how modifications to an experimental procedure will alter results.	
	7.13 pH and Solubility	**2.D** Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.	
	7.14 Free Energy of Dissolution	**4.D** Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 7. Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	7.3	**Manipulatives** Give groups of students containers that hold objects representing particles in an equilibrium mix (beads work well here). Each bead represents a molecule in a reversible synthesis reaction. The law of mass action is introduced, and students are asked to calculate K. Each group should get the same value for K, even though the number of particles in each container is different. Each group of students then gets a new container that represents a mixture not at equilibrium, and they calculate the ratio using the law of mass action. The concept of Q is introduced and then students determine if and how they could get the ratio of reactants and products to be equal to K by attaching or detaching beads.
2	7.4 7.5	**Identify Subtasks** Given a gaseous equilibrium process, have students construct the expression that can ultimately be used to calculate the K_p.
3	7.9 7.10	**Demo with Q&A** Prepare a solution of cobalt (II) chloride in dry ethanol. Demonstrate various methods to shift the equilibrium position: adding water, heating, cooling, layering with dry acetone, adding silver nitrate to precipitate chloride ions from solution, and measuring the temperature change of the solution as concentrated hydrochloric acid is added. As a class, have students analyze what each change does to the predominant species in the equilibrium mixture and then generalize patterns for Le Châtelier's principle.
4	7.11	**Post-Lab Discussion** After examining the K_{sp} tables for patterns (including ion charge, ionic radius, polyatomic vs. monoatomic ions, etc.), have students investigate the K_{sp} of lead (II) iodide. One drop of 0.1 M potassium iodide is added to 250 mL of 0.01 M lead (II) nitrate. A precipitate forms but then dissolves as it dissipates through the solution. Based on K_{sp}, have students calculate whether the precipitate should have formed and connect this calculation with what was initially observed. Have them determine how many milliliters of the 0.1 M KI solution would need to be added for a lasting precipitate to be formed. Then have them share their calculated values and agree as a class which is the best answer.

TOPIC 7.1

Introduction to Equilibrium

Required Course Content

ENDURING UNDERSTANDING

TRA-6

Some reactions can occur in both forward and reverse directions, sometimes proceeding in each direction simultaneously.

LEARNING OBJECTIVE

TRA-6.A

Explain the relationship between the occurrence of a reversible chemical or physical process, and the establishment of equilibrium, to experimental observations.

ESSENTIAL KNOWLEDGE

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.

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.

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.

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.

SUGGESTED SKILL

Argumentation

6.D

Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

SUGGESTED SKILL

Model Analysis

4.D

Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.

TOPIC 7.2

Direction of Reversible Reactions

Required Course Content

ENDURING UNDERSTANDING

TRA-6

Some reactions can occur in both forward and reverse directions, sometimes proceeding in each direction simultaneously.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
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.

TOPIC 7.3

Reaction Quotient and Equilibrium Constant

SUGGESTED SKILL

Representing Data and Phenomena

3.A

Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

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.A

Represent the reaction quotient Q_c or Q_p, for a reversible reaction, and the corresponding equilibrium expressions $K_c = Q_c$ or $K_p = Q_p$.

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 $K_p = Q_p$. As examples, for the reaction

$$\mathrm{aA + bB \rightleftharpoons cC + dD}$$

the equilibrium expression for (K_c, Q_c) is

EQN: $K_c = \dfrac{[\mathrm{C}]^c[\mathrm{D}]^d}{[\mathrm{A}]^a[\mathrm{B}]^b}$

and that for (K_p, Q_p) is

EQN: $K_p = \dfrac{(\mathrm{P_C})^c(\mathrm{P_D})^d}{(\mathrm{P_A})^a(\mathrm{P_B})^b}$

☒ **CONVERSION BETWEEN K_c AND K_p WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Conversion between K_c and K_p is an algorithm that does not deepen understanding of equilibrium. However, students should be aware of the conceptual differences and pay attention to whether K_c or K_p is used in an exam question.*

continued on next page

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 $K_p = Q_p$.

ESSENTIAL KNOWLEDGE

☒ **EQUILIBRIUM CALCULATIONS ON SYSTEMS WHERE A DISSOLVED SPECIES IS IN EQUILIBRIUM WITH THAT SPECIES IN THE GAS PHASE WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *The need to account for the relative volumes of the liquid and gas phase is complex in these mixed equilibria.*

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.

TOPIC 7.4

Calculating the Equilibrium Constant

SUGGESTED SKILL

Mathematical Routines

5.C

Explain the relationship between variables within an equation when one variable changes.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

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.B

Calculate K_c or K_p based on experimental observations of concentrations or pressures at equilibrium.

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.

SUGGESTED SKILL

Argumentation

6.D

Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 7.5

Magnitude of the Equilibrium Constant

Required Course Content

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.C

Explain the relationship between very large or very small values of K and the relative concentrations of chemical species at equilibrium.

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.

TOPIC 7.6

Properties of the Equilibrium Constant

Required Course Content

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.

TRA-7.D.2

When the stoichiometric coefficients of a reaction are multiplied by a factor c, K is raised to the power c.

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.

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.

SUGGESTED SKILL

Mathematical Routines

5.A

Identify quantities needed to solve a problem from given information (e.g., text, mathematical expressions, graphs, or tables).

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

SUGGESTED SKILL

Representing Data and Phenomena

3.A

Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 7.7

Calculating Equilibrium Concentrations

Required Course Content

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.

TOPIC 7.8

Representations of Equilibrium

SUGGESTED SKILL

Representing Data and Phenomena

3.C

Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).

Required Course Content

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.

SUGGESTED SKILL

Argumentation

6.F

Explain the connection between experimental results and chemical concepts, processes, or theories.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 13: Can We Make the Colors of the Rainbow? An Application of Le Châtelier's Principle**

TOPIC 7.9

Introduction to Le Châtelier's Principle

Required Course Content

ENDURING UNDERSTANDING

TRA-8

Systems at equilibrium respond to external stresses to offset the effect of the stress.

LEARNING OBJECTIVE

TRA-8.A

Identify the response of a system at equilibrium to an external stress, using Le Châtelier's principle.

ESSENTIAL KNOWLEDGE

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.

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.

TOPIC 7.10

Reaction Quotient and Le Châtelier's Principle

Required Course Content

ENDURING UNDERSTANDING

TRA-8

Systems at equilibrium respond to external stresses to offset the effect of the stress.

LEARNING OBJECTIVE

TRA-8.B

Explain the relationships between Q, K, and the direction in which a reversible reaction will proceed to reach equilibrium.

ESSENTIAL KNOWLEDGE

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.

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.

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 13: Can We Make the Colors of the Rainbow? An Application of Le Châtelier's Principle**

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

TOPIC 7.11

Introduction to Solubility Equilibria

Required Course Content

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.A

Calculate the solubility of a salt based on the value of K_{sp} for the salt.

ESSENTIAL KNOWLEDGE

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.

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.

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.

TOPIC 7.12
Common-Ion Effect

SUGGESTED SKILL

Question and Method

2.F

Explain how modifications to an experimental procedure will alter results.

Required Course Content

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.

SUGGESTED SKILL

Question and Method

2.D

Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 7.13

pH and Solubility

Required Course Content

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.

☒ **COMPUTATIONS OF SOLUBILITY AS A FUNCTION OF pH WILL NOT BE ASSESSED ON THE AP EXAM.**

TOPIC 7.14

Free Energy of Dissolution

SUGGESTED SKILL

Model Analysis

4.D

Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

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.

AP CHEMISTRY

UNIT 8

Acids and Bases

11–15%
AP EXAM WEIGHTING

~14–15
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 8

Multiple-choice: ~30 questions
Free-response: 1 question

- Long-answer

UNIT
8

11–15% AP EXAM WEIGHTING

~14–15 CLASS PERIODS

Acids and Bases

BIG IDEA 2
Structure and Properties **SAP**

- How are reactions involving acids and bases related to pH?
- How does your body maintain pH balance?

Developing Understanding

This unit builds on the content about chemical equilibrium studied in Unit 7. Chemical equilibrium plays an important role in acid-base chemistry and solubility. The proton-exchange reactions of acid-base chemistry are reversible reactions that reach equilibrium quickly, and much of acid-base chemistry can be understood by applying the principles of chemical equilibrium. Most acid-base reactions have either large or small values of K, which means qualitative conclusions regarding equilibrium state can often be drawn without extensive computations. The dissolution of a solid in a solvent can also be understood by applying the principles of chemical equilibrium because it is a reversible reaction that often reaches equilibrium quickly. In the final unit, the equilibrium constant is related to temperature and the difference in Gibbs free energy between the reactants and products.

Building the Science Practices

2.D **5.B** **5.C** **5.D** **5.F** **6.C** **6.D** **6.G**

In Unit 8, students will apply the explanations and calculations they learned in Unit 7 to the acid-base equilibrium system. Students will collect titration data and develop titration curves to represent a variety of acid-base systems. They will analyze these titration curves to describe the similarities and differences between a strong acid-strong base and a weak acid-strong base titration, identify the equivalence points and the half-equivalence points, and identify the buffering regions of the curves. Students will use the information presented graphically in the titration curves to complete calculations to find the equilibrium constant for the reactions (K_a or K_b), determine the concentration of an unknown, and support claims about how a particular buffer system may work when an acid or base is introduced. From these calculations and what is known about the chemical system, students will then develop explanations for how potential sources of error may have affected experimental results and associated calculations.

Preparing for the AP Exam

On the AP Exam, students must be able to use experimental data to make calculations and support claims. Students often struggle with questions that require them to use titration curves to identify the equivalence and half-equivalence points or to complete calculations or estimations of either the concentration or pH of an unknown at a particular point on the curve. They also struggle to justify the selection of an appropriate indicator for the end point of the titration. In these situations, students can struggle with unit conversion, or they can confuse half-equivalence, equivalence, and endpoint. Or, they may struggle to understand what general types of titration curves represent. Teachers can provide students with multiple opportunities to describe why titration curves have characteristic shapes for certain acid-base equilibrium systems. Teachers can also provide opportunities to choose and implement mathematical routines to manipulate and interpret titration data and connect that interpretation to chemistry concepts. Practicing using the half-titration point helps to visualize and clarify ratios between acid/conjugate base.

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~14–15 CLASS PERIODS
SAP-9	**8.1** Introduction to Acids and Bases	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	8.2 pH and pOH of Strong Acids and Bases	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	8.3 Weak Acid and Base Equilibria	**5.C** Explain the relationship between variables within an equation when one variable changes.	
	8.4 Acid-Base Reactions and Buffers	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	8.5 Acid-Base Titrations	**5.D** Identify information presented graphically to solve a problem.	
	8.6 Molecular Structure of Acids and Bases	**6.C** Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.	
SAP-10	**8.7** pH and pK_a	**2.D** Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.	
	8.8 Properties of Buffers	**6.D** Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	
	8.9 Henderson-Hasselbalch Equation	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	8.10 Buffer Capacity	**6.G** Explain how potential sources of experimental error may affect the experimental results.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 8.
Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	8.2 8.3	**Post-Lab Discussion** Rainbow Acid Indicator (Flinn Scientific Item U0012) is added to 0.001 M solutions of HCl, H_2SO_4, and $HC_2H_3O_2$. Have students reason out why the pH values are not the same, and introduce the concept of K_a. Then have them calculate the pH of each solution to explain their earlier observations. Percent ionization is discussed and how ICE charts reflect the percent ionization is explained.
2	8.5	**Post-Lab Discussion** After collecting data on a weak acid/strong base titration, have students create a titration curve (pH as a function of the volume of base added). Then have them identify relative points on the graph based on group discussion (e.g., equivalence point).
3	8.8	**Demo with Q&A** Add an Alka-Seltzer tablet to 200 mL of water and pour the resulting solution into three small beakers. Add deionized water to three more beakers. Add universal indicator to all six beakers and then add strong acids and strong bases to each beaker to demonstrate buffering ability and buffer capacity. Have students develop particulate-level drawings to illustrate what is happening in the beakers in the context of "buffering ability."
4	8.9 8.10	**Simulations** Using a ChemCollective virtual lab, ask students to develop a buffer that will have a particular pH after an amount of strong acid is added.

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- The Exam > **2017 Chief Reader Report**

TOPIC 8.1

Introduction to Acids and Bases

Required Course Content

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

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.

ESSENTIAL KNOWLEDGE

SAP-9.A.1

The concentrations of hydronium ion and hydroxide ion are often reported as pH and pOH, respectively.

EQN: $\mathrm{pH} = -\log[\mathrm{H_3O^+}]$

EQN: $\mathrm{pOH} = -\log[\mathrm{OH^-}]$

The terms "hydrogen ion" and "hydronium ion" and the symbols $\mathrm{H^+}(aq)$ and $\mathrm{H_3O^+}(aq)$ are often used interchangeably for the aqueous ion of hydrogen. Hydronium ion and $\mathrm{H_3O^+}(aq)$ are preferred, but $\mathrm{H^+}(aq)$ is also accepted on the AP Exam.

SAP-9.A.2

Water autoionizes with an equilibrium constant K_w.

EQN: $K_w = [\mathrm{H_3O^+}][\mathrm{OH^-}] = 1.0 \times 10^{-14}$ at 25°C

SAP-9.A.3

In pure water, $\mathrm{pH} = \mathrm{pOH}$ is called a neutral solution. At 25°C, $\mathrm{p}K_w = 14.0$ and thus $\mathrm{pH} = \mathrm{pOH} = 7.0$.

EQN: $\mathrm{p}K_w = 14 = \mathrm{pH} + \mathrm{pOH}$ at 25°C

SAP-9.A.4

The value of K_w is temperature dependent, so the pH of pure, neutral water will deviate from 7.0 at temperatures other than 25°C.

TOPIC 8.2

pH and pOH of Strong Acids and Bases

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

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

SAP-9.B

Calculate pH and pOH based on concentrations of all species in a solution of a strong acid or a strong base.

ESSENTIAL KNOWLEDGE

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.

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.

SUGGESTED SKILL

Mathematical Routines

5.C

Explain the relationship between variables within an equation when one variable changes.

TOPIC 8.3

Weak Acid and Base Equilibria

Required Course Content

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

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.

ESSENTIAL KNOWLEDGE

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.

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 $\mathrm{p}K_a$. The pH of a weak acid solution can be determined from the initial acid concentration and the $\mathrm{p}K_a$.

EQN: $K_a = \dfrac{[H_3O^+][A^-]}{[HA]}$

EQN: $\mathrm{p}K_a = -\log K_a$

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LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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.

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.

EQN: $K_b = \frac{[OH^-][HB^+]}{[B]}$

EQN: $pK_b = -\log K_b$

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).

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

TOPIC 8.4

Acid-Base Reactions and Buffers

Required Course Content

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

SAP-9.D

Explain the relationship among the concentrations of major species in a mixture of weak and strong acids and bases.

ESSENTIAL KNOWLEDGE

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.

SAP-9.D.2

When a weak acid and a strong base are mixed, they react quantitatively in a reaction represented by the equation:

$$HA(aq) + OH^-(aq) \rightleftharpoons A^-(aq)\ H_2O(l).$$

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:

$$A^-(aq) + H_2O(l) \rightleftharpoons HA(aq) + OH^-(aq).$$

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LEARNING OBJECTIVE

SAP-9.D

Explain the relationship among the concentrations of major species in a mixture of weak and strong acids and bases.

ESSENTIAL KNOWLEDGE

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:

$$\mathrm{B}(aq) + \mathrm{H_3O^+}(aq) \rightleftharpoons \mathrm{HB^+}(aq) + \mathrm{H_2O}(l).$$

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:

$$\mathrm{HB^+}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{B}(aq) + \mathrm{H_3O^+}(aq).$$

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:

$$\mathrm{HA}(aq) + \mathrm{B}(aq) \rightleftharpoons \mathrm{A^-}(aq) + \mathrm{HB^+}(aq).$$

SUGGESTED SKILL

Mathematical Routines

5.D

Identify information presented graphically to solve a problem.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 14: How Do the Structure and the Initial Concentration of an Acid and a Base Influence the pH of the Resultant Solution During a Titration?**

TOPIC 8.5

Acid-Base Titrations

Required Course Content

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

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.

ESSENTIAL KNOWLEDGE

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.

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.

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 $[\mathrm{HA}] = [\mathrm{A}^-]$. Because $\mathrm{pH} = \mathrm{p}K_a$ when the conjugate acid and base have equal concentrations, the $\mathrm{p}K_a$ can be determined from the pH at the half-equivalence point in a titration.

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LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

SAP-9.E.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.

☒ **COMPUTATION OF THE CONCENTRATION OF EACH SPECIES PRESENT IN THE TITRATION CURVE FOR POLYPROTIC ACIDS WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Such computations for titration of monoprotic acids are within the scope of the course, as is qualitative reasoning regarding what species are present in large versus small concentrations at any point in titration of a polyprotic acid. However, additional computations of the concentration of each species present in the titration curve for polyprotic acids may encourage algorithmic calculations rather than deepen understanding.*

SUGGESTED SKILL

Argumentation

6.C

Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.

TOPIC 8.6

Molecular Structure of Acids and Bases

Required Course Content

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

SAP-9.F

Explain the relationship between the strength of an acid or base and the structure of the molecule or ion.

ESSENTIAL KNOWLEDGE

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, $HClO_4$, H_2SO_4, and HNO_3) 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.

TOPIC 8.7

pH and pK_a

SUGGESTED SKILL

Question and Method

2.D

Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

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.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.

ESSENTIAL KNOWLEDGE

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 $pH < \text{acid } pK_a$, the acid form has a higher concentration than the base form. When solution $pH > \text{acid } pK_a$, the base form has a higher concentration than the acid form.

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.

SUGGESTED SKILL

Argumentation

6.D

Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 15: To What Extent Do Common Household Products Have Buffering Activity?**

TOPIC 8.8

Properties of Buffers

Required Course Content

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.

TOPIC 8.9

Henderson-Hasselbalch Equation

Required Course Content

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.

EQN: $\mathrm{pH} = \mathrm{p}K_a + \log\dfrac{[A^-]}{[HA]}$

☒ **COMPUTATION OF THE CHANGE IN pH RESULTING FROM THE ADDITION OF AN ACID OR A BASE TO A BUFFER WILL NOT BE ASSESSED ON THE AP EXAM.**

☒ **DERIVATION OF THE HENDERSON-HASSELBALCH EQUATION WILL NOT BE ASSESSED ON THE AP EXAM.**

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 9: Can the Individual Components of Quick Ache Relief Be Used to Resolve Consumer Complaints?**

SUGGESTED SKILL

Argumentation

6.G

Explain how potential sources of experimental error may affect the experimental results.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 16: The Preparation and Testing of an Effective Buffer: How Do Components Influence a Buffer's pH and Capacity?**

TOPIC 8.10

Buffer Capacity

Required Course Content

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.

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.

AP CHEMISTRY

UNIT 9

Applications of Thermodynamics

7–9%
AP EXAM WEIGHTING

~10–13
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and skills.

Personal Progress Check 9

Multiple-choice: ~30 questions
Free-response: 2 questions

- Short-answer
- Long-answer

UNIT
9

7–9% AP EXAM WEIGHTING

~10–13 CLASS PERIODS

Applications of Thermodynamics

BIG IDEA 4

Energy **ENE**

- How does water flow uphill?
- How is the favorability of a chemical or physical transformation determined?
- How is electrical energy generated using chemical reactions?

Developing Understanding

This unit allows students to connect principles and calculations across Units 5–8. The thermodynamics of a chemical reaction is connected to both the structural aspects of the reaction and the macroscopic outcomes of the reaction. All changes in matter involve some form of energy change. One key determinant of chemical transformations is the change in potential energy that results from changes in electrostatic forces. Chemical systems undergo three main processes that change their energy: heating/cooling, phase transitions, and chemical reactions. Applying the laws of thermodynamics will allow students to describe the essential role of energy and explain and predict the direction of changes in matter.

Building the Science Practices

5.F 6.D 6.E

To achieve success in AP Chemistry and in Unit 9 specifically, students must connect principles and calculations across the areas of kinetics, thermodynamics, equilibrium, and electrochemistry to explain and support claims about what is happening in chemical systems. Sometimes support of such claims comes from students being able to estimate an approximate value of a required characteristic of a chemical system rather than use a routine application of an algorithm.

Students are introduced to entropy as a factor that is necessary to explain why some endothermic reactions occur in spite of the lower energy that products may have in exothermic changes. Students will use particulate representations and graphical distribution of kinetic energy to describe the increase in entropy with increasing temperature. In addition, students will explore how to use Gibbs free energy for determining the thermodynamic favorability by considering the change in both enthalpy and entropy. Students will use the concepts of thermodynamics to generate more comprehensive claims about what is happening in a galvanic or electrolytic cell.

Preparing for the AP Exam

On the AP Exam, students must be able to provide an appropriate explanation of the connection between entropy, enthalpy, and Gibbs free energy and the thermodynamic favorability of a chemical reaction. Students often struggle with questions that require them to reason about whether enthalpy, entropy, or both drive a reaction. They will state that both enthalpy and entropy drive the reaction by using the equation for Gibbs free energy instead of reasoning about which might be more of a driving factor than the other. Further, some students fail to connect macroscopic observational data to the concepts of entropy and enthalpy to support claims about which concept was driving the reaction. Teachers can ensure that students understand that the first step in making thermodynamic favorability predictions is to define and interrelate enthalpy, entropy, and Gibbs free energy in relation to driving chemical or physical processes. Students should be shown how the concepts of kinetics, equilibrium, and thermodynamics are connected in order to explain why thermodynamically favorable reactions might produce small concentrations of product and why unfavorable reactions can produce large concentrations of product.

UNIT 9
Applications of Thermodynamics

UNIT AT A GLANCE

Enduring Understanding	Topic	Suggested Skill	Class Periods ~10–13 CLASS PERIODS
ENE-4	**9.1** Introduction to Entropy	**6.C** Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.	
	9.2 Absolute Entropy and Entropy Change	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	9.3 Gibbs Free Energy and Thermodynamic Favorability	**6.E** Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.	
	9.4 Thermodynamic and Kinetic Control	**6.E** Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.	
ENE-5	**9.5** Free Energy and Equilibrium	**6.D** Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	
	9.6 Coupled Reactions	**4.D** Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.	
ENE-6	**9.7** Galvanic (Voltaic) and Electrolytic Cells	**2.F** Explain how modifications to an experimental procedure will alter results.	
	9.8 Cell Potential and Free Energy	**5.F** Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	9.9 Cell Potential Under Nonstandard Conditions	**6.D** Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	
	9.10 Electrolysis and Faraday's Law	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 9. Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 197 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	9.3	**Think-Pair-Share** Given a problem pertaining to thermodynamic favorability, have students think through how enthalpy and/or entropy is driving the thermodynamic favorability of the reaction. Have them pair up and explain their reasoning for whether or not the reaction is thermodynamically favorable and what is driving that favorability. After the pairs have discussed their responses, have them share with other pairs to get feedback on their rationale.
2	9.7	**Demo with Q&A** Construct a simple battery by submerging two electrodes (Mg and Cu) into orange juice and attaching it to the battery compartment of a quartz clock. Instruct students to ask as many questions as they can while the clock is running. Allow the clock to run for as long as possible and then examine the magnesium anode after a day to see if it corrodes away. As a class, examine the table of standard reduction potentials and discuss where the electrons are coming from and going to in order to power the clock.
3	9.10	**Critique Reasoning** Have students mass a new penny with an analytical balance. They attach the penny to the negative electrode, which is attached to a 9-volt battery. A zinc strip is attached to the positive electrode. The penny is submerged for 10 minutes in a 1.0 M NaOH solution with zinc dust and the zinc electrode. Students dry the penny and mass it again. Using Faraday’s laws, have them calculate the current that must have been delivered to plate the zinc onto the penny. Then have student pairs share and peer review each other’s reasoning.

SUGGESTED SKILL

Argumentation

6.C

Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.

AVAILABLE RESOURCES

- Classroom Resource > **Units in Thermochemical Calculations**

TOPIC 9.1

Introduction to Entropy

Required Course Content

ENDURING UNDERSTANDING

ENE-4

Some chemical or physical processes cannot occur without intervention.

LEARNING OBJECTIVE

ENE-4.A

Identify the sign and relative magnitude of the entropy change associated with chemical or physical processes.

ESSENTIAL KNOWLEDGE

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.

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.

TOPIC 9.2

Absolute Entropy and Entropy Change

Required Course Content

ENDURING UNDERSTANDING

ENE-4

Some chemical or physical processes cannot occur without intervention.

LEARNING OBJECTIVE

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.

ESSENTIAL KNOWLEDGE

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: $\Delta S^{\circ}_{reaction} = \Sigma S^{\circ}_{products} - \Sigma S^{\circ}_{reactants}$

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- Classroom Resource > **Units in Thermochemical Calculations**

TOPIC 9.3

Gibbs Free Energy and Thermodynamic Favorability

SUGGESTED SKILL

Argumentation

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**
- The Exam > **2017 Chief Reader Report**

Required Course Content

ENDURING UNDERSTANDING

ENE-4

Some chemical or physical processes cannot occur without intervention.

LEARNING OBJECTIVE

ENE-4.C

Explain whether a physical or chemical process is thermodynamically favored based on an evaluation of ΔG°.

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°.

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 $\Delta G^\circ < 0$. The phrase “thermodynamically favored” is preferred instead so that common misunderstandings (equating “spontaneous” with “suddenly” or “without cause”) can be avoided. When $\Delta G^\circ < 0$ for the process, it is said to be thermodynamically favored.

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: $\Delta G^\circ_{reaction} = \Sigma \Delta G_f^\circ{}_{products} - \Sigma \Delta G_f^\circ{}_{reactants}$

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LEARNING OBJECTIVE

ENE-4.C

Explain whether a physical or chemical process is thermodynamically favored based on an evaluation of ΔG°.

ESSENTIAL KNOWLEDGE

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.

ENE-4.C.5

Knowing the values of ΔH° and ΔS° for a process at a given temperature allows ΔG° to be calculated directly.

EQN: $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$

ENE-4.C.6

In general, the temperature conditions for a process to be thermodynamically favored ($\Delta G^\circ < 0$) can be predicted from the signs of ΔH° and ΔS° as shown in the table below:

ΔH°	ΔS°	Symbols	$\Delta G^\circ < 0$, favored at:
< 0	> 0	$< >$	all T
> 0	< 0	$> <$	no T
> 0	> 0	$> >$	high T
< 0	< 0	$< <$	low T

In cases where $\Delta H^\circ < 0$ and $\Delta S^\circ > 0$, no calculation of ΔG° is necessary to determine that the process is thermodynamically favored ($\Delta G^\circ < 0$). In cases where $\Delta H^\circ > 0$ and $\Delta S^\circ < 0$, no calculation of ΔG° is necessary to determine that the process is thermodynamically unfavored ($\Delta G^\circ > 0$).

SUGGESTED SKILL

Argumentation

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

AVAILABLE RESOURCES

- Classroom Resource > **Alternative Approaches to Teaching Traditional Topics**

TOPIC 9.4

Thermodynamic and Kinetic Control

Required Course Content

ENDURING UNDERSTANDING

ENE-4

Some chemical or physical processes cannot occur without intervention.

LEARNING OBJECTIVE

ENE-4.D

Explain, in terms of kinetics, why a thermodynamically favored reaction might not occur at a measurable rate.

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.

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.

TOPIC 9.5

Free Energy and Equilibrium

SUGGESTED SKILL

Argumentation

6.D

Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

ENDURING UNDERSTANDING

ENE-5

The relationship between $\Delta G°$ and K can be used to determine favorability of a chemical or physical transformation.

LEARNING OBJECTIVE

ENE-5.A

Explain whether a process is thermodynamically favored using the relationships between K, $\Delta G°$, and T.

ESSENTIAL KNOWLEDGE

ENE-5.A.1

The phrase "thermodynamically favored" ($\Delta G° < 0$) means that the products are favored at equilibrium ($K > 1$).

ENE-5.A.2

The equilibrium constant is related to free energy by the equations

EQN: $K = e^{-\Delta G°/RT}$

and

EQN: $\Delta G° = -RT \ln K$.

ENE-5.A.3

Connections between K and $\Delta G°$ can be made qualitatively through estimation. When $\Delta G°$ is near zero, the equilibrium constant will be close to 1. When $\Delta G°$ is much larger or much smaller than RT, the value of K deviates strongly from 1.

ENE-5.A.4

Processes with $\Delta G° < 0$ favor products (i.e., $K > 1$) and those with $\Delta G° > 0$ favor reactants (i.e., $K < 1$).

SUGGESTED SKILL

Model Analysis

4.D

Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.

TOPIC 9.6
Coupled Reactions

Required Course Content

ENDURING UNDERSTANDING

ENE-5

The relationship between $\Delta G°$ and K can be used to determine favorability of a chemical or physical transformation.

LEARNING OBJECTIVE

ENE-5.B

Explain the relationship between external sources of energy or coupled reactions and their ability to drive thermodynamically unfavorable processes.

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.

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 $\Delta G° < 0$.

TOPIC 9.7

Galvanic (Voltaic) and Electrolytic Cells

SUGGESTED SKILL

Question and Method

2.F

Explain how modifications to an experimental procedure will alter results.

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

Required Course Content

ENDURING UNDERSTANDING

ENE-6

Electrical energy can be generated by chemical reactions.

LEARNING OBJECTIVE

ENE-6.A

Explain the relationship between the physical components of an electrochemical cell and the overall operational principles of the cell.

ESSENTIAL KNOWLEDGE

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.

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.

ENE-6.A.3

For all electrochemical cells, oxidation occurs at the anode and reduction occurs at the cathode.

☒ **LABELING AN ELECTRODE AS POSITIVE OR NEGATIVE WILL NOT BE ASSESSED ON THE AP EXAM.**

Rationale: *Sign conventions vary depending on the type of electrochemical cell, even though oxidation always occurs at the anode.*

SUGGESTED SKILL

Mathematical Routines

5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

AVAILABLE RESOURCES

- Classroom Resource > **Quantitative Skills in the AP Sciences**

TOPIC 9.8

Cell Potential and Free Energy

Required Course Content

ENDURING UNDERSTANDING

ENE-6

Electrical energy can be generated by chemical reactions.

LEARNING OBJECTIVE

ENE-6.B

Explain whether an electrochemical cell is thermodynamically favored, based on its standard cell potential and the constituent half-reactions within the cell.

ESSENTIAL KNOWLEDGE

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).

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.

ENE-6.B.3

ΔG° (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° involves a thermodynamically favored reaction, and a cell with a negative E° involves a thermodynamically unfavored reaction.

EQN: $\Delta G^\circ = -nFE^\circ$

TOPIC 9.9

Cell Potential Under Nonstandard Conditions

SUGGESTED SKILL

Argumentation

6.D

Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.

Required Course Content

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.

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.

ENE-6.C.3

The standard cell potential E° 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 E°. Deviations from standard conditions that take the cell closer to equilibrium than $Q = 1$ will decrease the magnitude of the cell potential relative to E°. In concentration cells, the direction of spontaneous electron flow can be determined by considering the direction needed to reach equilibrium.

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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.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: $E = E^{\circ} - (RT/nF) \ln Q$

to solve problems.

TOPIC 9.10

Electrolysis and Faraday's Law

SUGGESTED SKILL

Mathematical Routines

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

Required Course Content

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: $I = q/t$