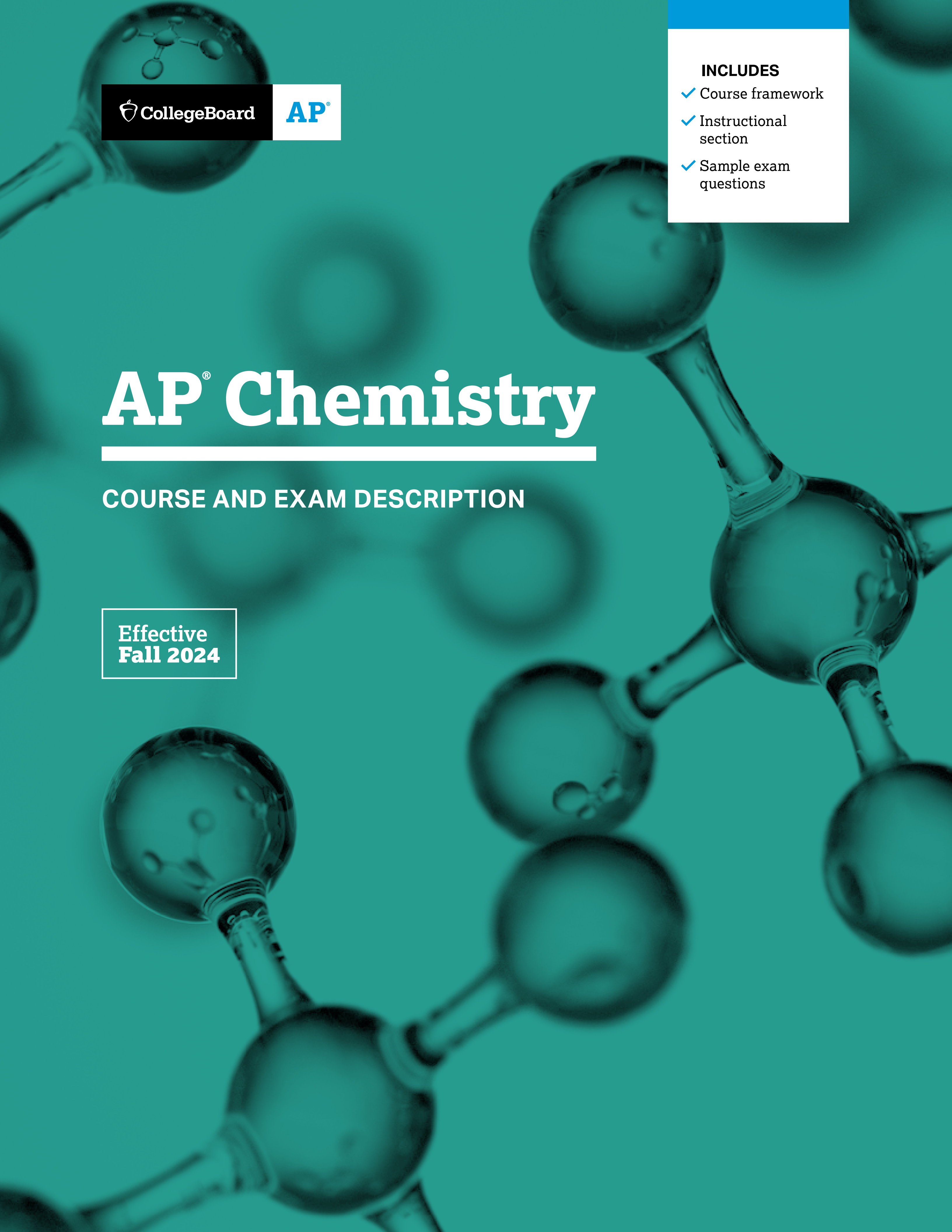

CollegeBoard AP

INCLUDES

- ✓ Course framework
- ✓ Instructional section
- ✓ Sample exam questions

AP® Chemistry

COURSE AND EXAM DESCRIPTION

Effective
Fall 2024

AP® Chemistry

COURSE AND EXAM DESCRIPTION

Effective
Fall 2024

AP COURSE AND EXAM DESCRIPTIONS ARE UPDATED PERIODICALLY

Please visit AP Central (apcentral.collegeboard.org) to determine whether a more recent course and exam description is available.

What AP® Stands For

Thousands of Advanced Placement teachers have contributed to the principles articulated here. These principles are not new; they are, rather, a reminder of how AP already works in classrooms nationwide. The following principles are designed to ensure that teachers' expertise is respected, required course content is understood, and that students are academically challenged and free to make up their own minds.

1. AP stands for clarity and transparency. Teachers and students deserve clear expectations. The Advanced Placement Program makes public its course frameworks and sample assessments. Confusion about what is permitted in the classroom disrupts teachers and students as they navigate demanding work.
2. AP is an unflinching encounter with evidence. AP courses enable students to develop as independent thinkers and to draw their own conclusions. Evidence and the scientific method are the starting place for conversations in AP courses.
3. AP opposes censorship. AP is animated by a deep respect for the intellectual freedom of teachers and students alike. If a school bans required topics from their AP courses, the AP Program removes the AP designation from that course and its inclusion in the AP Course Ledger provided to colleges and universities. For example, the concepts of evolution are at the heart of college biology, and a course that neglects such concepts does not pass muster as AP Biology.
4. AP opposes indoctrination. AP students are expected to analyze different perspectives from their own, and no points on an AP Exam are awarded for agreement with any specific viewpoint. AP students are not required to feel certain ways about themselves or the course content. AP courses instead develop students' abilities to assess the credibility of sources, draw conclusions, and make up their own minds.

   As the AP English Literature course description states: "AP students are not expected or asked to subscribe to any one specific set of cultural or political values, but are expected to have the maturity to analyze perspectives different from their own and to question the meaning, purpose, or effect of such content within the literary work as a whole."
5. AP courses foster an open-minded approach to the histories and cultures of different peoples. The study of different nationalities, cultures, religions, races, and ethnicities is essential within a variety of academic disciplines. AP courses ground such studies in primary sources so that students can evaluate experiences and evidence for themselves.
6. Every AP student who engages with evidence is listened to and respected. Students are encouraged to evaluate arguments but not one another. AP classrooms respect diversity in backgrounds, experiences, and viewpoints. The perspectives and contributions of the full range of AP students are sought and considered. Respectful debate of ideas is cultivated and protected; personal attacks have no place in AP.
7. AP is a choice for parents and students. Parents and students freely choose to enroll in AP courses. Course descriptions are available online for parents and students to inform their choice. Parents do not define which college-level topics are suitable within AP courses; AP course and exam materials are crafted by committees of professors and other expert educators in each field. AP courses and exams are then further validated by the American Council on Education and studies that confirm the use of AP scores for college credits by thousands of colleges and universities nationwide.

The AP Program encourages educators to review these principles with parents and students so they know what to expect in an AP course. Advanced Placement is always a choice, and it should be an informed one. AP teachers should be given the confidence and clarity that once parents have enrolled their child in an AP course, they have agreed to a classroom experience that embodies these principles.

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Acknowledgments

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About AP

The Advanced Placement® Program (AP®) enables willing and academically prepared students to pursue college-level studies—with the opportunity to earn college credit, advanced placement, or both—while still in high school. Through AP courses in 39 subjects, each culminating in a challenging exam, students learn to think critically, construct solid arguments, and see many sides of an issue—skills that prepare them for college and beyond. Taking AP courses demonstrates to college admission officers that students have sought the most challenging curriculum available to them, and research indicates that students who score a 3 or higher on an AP Exam typically experience greater academic success in college and are more likely to earn a college degree than non-AP students. Each AP teacher's syllabus is evaluated and approved by faculty from some of the nation's leading colleges and universities, and AP Exams are developed and scored by college faculty and experienced AP teachers. Most four-year colleges and universities in the United States grant credit, advanced placement, or both on the basis of successful AP Exam scores—more than 3,300 institutions worldwide annually receive AP scores.

AP Course Development

In an ongoing effort to maintain alignment with best practices in college-level learning, AP courses and exams emphasize challenging, research-based curricula aligned with higher education expectations.

Individual teachers are responsible for designing their own curriculum for AP courses, selecting appropriate college-level readings, assignments, and resources. This course and exam description presents the content and skills that are the focus of the corresponding college course and that appear on the AP Exam. It also organizes the content and skills into a series of units that represent a sequence found in widely adopted college textbooks and that many AP teachers have told us they follow in order to focus their instruction. The intention of this publication is to respect teachers' time and expertise by providing a roadmap that they can modify and adapt to their local priorities and preferences. Moreover, by organizing the AP course content and skills into units, the AP Program is able to provide teachers and students with free formative assessments—Progress Checks—that teachers can assign throughout the year to measure student progress as they acquire content knowledge and develop skills.

Enrolling Students: Equity and Access

The AP Program strongly encourages educators to make equitable access a guiding principle for their AP programs by giving all willing and academically prepared students the opportunity to participate in AP. We encourage the elimination of barriers that restrict access to AP for students from ethnic, racial, and socioeconomic groups that have been traditionally underserved. The AP Program also believes that all students should have access to academically challenging coursework before they enroll in AP classes, which can prepare them for AP success. It is only through a commitment to equitable preparation and access that true equity and excellence can be achieved.

Offering AP Courses: The AP Course Audit

The AP Program unequivocally supports the principle that each school implements its own curriculum that will enable students to develop the content understandings and skills described in the course framework.

While the unit sequence represented in this publication is optional, the AP Program does have a short list of curricular and resource requirements that must be fulfilled before a school can label a course "Advanced Placement" or "AP." Schools wishing to offer AP courses must participate in the AP Course Audit, a process through which AP teachers' course materials are reviewed by college faculty. The AP Course Audit was created to provide teachers and administrators with clear guidelines on curricular and resource requirements for AP courses and to help colleges and universities validate courses marked "AP" on students' transcripts. This process ensures that AP teachers' courses meet or exceed the curricular and resource expectations that college and secondary school faculty have established for college-level courses.

The AP Course Audit form is submitted by the AP teacher and the school principal (or designated administrator) to confirm awareness and understanding of the curricular and resource requirements. A syllabus or course outline, detailing how course requirements are met, is submitted by the AP teacher for review by college faculty.

Please visit **collegeboard.org/apcourseaudit** for more information to support the preparation and submission of materials for the AP Course Audit.

How the AP Program Is Developed

The scope of content for an AP course and exam is derived from an analysis of hundreds of syllabi and course offerings of colleges and universities. Using this research and data, a committee of college faculty and expert AP teachers work within the scope of the corresponding college course to articulate what students should know and be able to do upon the completion of the AP course. The resulting course framework is the heart of this course and exam description and serves as a blueprint of the content and skills that can appear on an AP Exam.

The AP Test Development Committees are responsible for developing each AP Exam, ensuring the exam questions are aligned to the course framework. The AP Exam development process is a multiyear endeavor; all AP Exams undergo extensive review, revision, piloting, and analysis to ensure that questions are accurate, fair, and valid, and that there is an appropriate spread of difficulty across the questions.

Committee members are selected to represent a variety of perspectives and institutions (public and private, small and large schools and colleges), and a range of gender, racial/ethnic, and regional groups. A list of each subject's current AP Test Development Committee members is available on **apcentral.collegeboard.org**.

Throughout AP course and exam development, College Board gathers feedback from various stakeholders in both secondary schools and higher education institutions. This feedback is carefully considered to ensure that AP courses and exams are able to provide students with a college-level learning experience and the opportunity to demonstrate their qualifications for advanced placement or college credit.

How AP Exams Are Scored

The exam scoring process, like the course and exam development process, relies on the expertise of both AP teachers and college faculty. While multiple-choice questions are scored by machine, the free-response questions and through-course performance assessments, as applicable, are scored by thousands of college faculty and expert AP teachers. Most are scored at the annual AP Reading, while a small portion is scored online. All AP Readers are thoroughly trained, and their work is monitored throughout the Reading for fairness and consistency. In each subject, a highly respected college faculty member serves as Chief Faculty Consultant and, with the help of AP Readers in leadership positions, maintains the accuracy of the scoring standards. Scores on the free-response questions and performance assessments are weighted and combined with the results of the computer-scored multiple-choice questions, and this raw score is converted into a composite AP score on a 1–5 scale.

AP Exams are **not** norm-referenced or graded on a curve. Instead, they are criterion-referenced, which means that every student who meets the criteria for an AP score of 2, 3, 4, or 5 will receive that score, no matter how many students that is. The criteria for the number of points students must earn on the AP Exam to receive scores of 3, 4, or 5—the scores that research consistently validates for credit and placement purposes—include:

- The number of points successful college students earn when their professors administer AP Exam questions to them.
- Performance that researchers have found to be predictive of an AP student succeeding when placed into a subsequent higher-level college course.
- The number of points college faculty indicate, after reviewing each AP question, that they expect is necessary to achieve each AP grade level.

Using and Interpreting AP Scores

The extensive work done by college faculty and AP teachers in the development of the course and exam and throughout the scoring process ensures that AP Exam scores accurately represent students' achievement in the equivalent college course. Frequent and regular research studies establish the validity of AP scores as follows:

AP Score	Credit Recommendation	College Grade Equivalent
5	Extremely well qualified	A
4	Well qualified	A–, B+, B
3	Qualified	B–, C+, C
2	Possibly qualified	n/a
1	No recommendation	n/a

While colleges and universities are responsible for setting their own credit and placement policies, most private colleges and universities award credit and/or advanced placement for AP scores of 3 or higher. Additionally, most states in the U.S. have adopted statewide credit policies that ensure college credit for scores of 3 or higher at public colleges and universities. To confirm a specific college's AP credit/placement policy, a search engine is available at **apstudent.org/creditpolicies**.

BECOMING AN AP READER

Each June, thousands of AP teachers and college faculty members from around the world gather for seven days in multiple locations to evaluate and score the free-response sections of the AP Exams. Ninety-eight percent of surveyed educators who took part in the AP Reading say it was a positive experience.

There are many reasons to consider becoming an AP Reader, including opportunities to:

- **Bring positive changes to the classroom:** Surveys show that the vast majority of returning AP Readers—both high school and college educators—make improvements to the way they teach or score because of their experience at the AP Reading.
- **Gain in-depth understanding of AP Exam and AP scoring standards:** AP Readers gain exposure to the quality and depth of the responses from the entire pool of AP Exam takers, and thus are better able to assess their students' work in the classroom.
- **Receive compensation:** AP Readers are compensated for their work during the Reading. Expenses, lodging, and meals are covered for Readers who travel.
- **Score from home:** AP Readers have online distributed scoring opportunities for certain subjects. Check **collegeboard.org/apreading** for details.
- **Earn Continuing Education Units (CEUs):** AP Readers earn professional development hours and CEUs that can be applied to PD requirements by states, districts, and schools.

How to Apply

Visit **collegeboard.org/apreading** for eligibility requirements and to start the application process.

AP Resources and Supports

By completing a simple class selection process at the start of the school year, teachers and students receive access to a robust set of classroom resources.

AP Classroom

AP Classroom is a dedicated online platform designed to support teachers and students throughout their AP experience. The platform provides a variety of powerful resources and tools to provide yearlong support to teachers and students, offering opportunities to give and get meaningful feedback on student progress.

UNIT GUIDES

Appearing in this publication and on AP Classroom, these planning guides outline all required course content and skills, organized into commonly taught units. Each Unit Guide suggests a sequence and pacing of content, scaffolds skill instruction across units, organizes content into topics, and provides tips on taking the AP Exam.

PROGRESS CHECKS

Formative AP questions for every unit provide feedback to students on the areas where they need to focus. Available online, Progress Checks measure knowledge and skills through multiple-choice questions with rationales to explain correct and incorrect answers, and free-response questions with scoring information. Because the Progress Checks are formative, the results of these assessments cannot be used to evaluate teacher effectiveness or assign letter grades to students, and any such misuses are grounds for losing school authorization to offer AP courses.*

REPORTS

Reports provides teachers with a one-stop shop for student results on all assignment types, including Progress Checks. Teachers can view class trends and see where students struggle with content and skills that will be assessed on the AP Exam. Students can view their own progress over time to improve their performance before the AP Exam.

QUESTION BANK

The Question Bank is a searchable library of all AP questions that teachers use to build custom practice for their students. Teachers can create and assign assessments with formative topic questions or questions from practice or released AP Exams.

Class Section Setup and Enrollment

- Teachers and students sign in to or create their College Board accounts.
- Teachers confirm that they have added the course they teach to their AP Course Audit account and have had it approved by their school's administrator.
- Teachers or AP coordinators, depending on who the school has decided is responsible, set up class sections so students can access AP resources and have exams ordered on their behalf.
- Students join class sections with a join code provided by their teacher or AP coordinator.
- Students will be asked for additional information upon joining their first class section.

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* To report misuses, please call, 877-274-6474 (International: 212-632-1781).

Instructional Model

Integrating AP resources throughout the course can help students develop skills and conceptual understandings. The instructional model outlined below shows possible ways to incorporate AP resources into the classroom.

Plan

Teachers may consider the following approaches as they plan their instruction before teaching each unit.

- Review the overview at the start of each **Unit Guide** to identify essential questions, conceptual understandings, and skills for each unit.
- Use the **Unit at a Glance** table to identify related topics that build toward a common understanding, and then plan appropriate pacing for students.
- Identify useful strategies in the **Instructional Approaches** section to help teach the concepts and skills.

Teach

When teaching, supporting resources could be used to build students' conceptual understanding and their mastery of skills.

- Use the topic pages in the **Unit Guides** to identify the required content.
- Integrate the content with a skill, considering any appropriate scaffolding.
- Employ any of the instructional strategies previously identified.
- Use the available resources, including **AP Daily**, on the topic pages to bring a variety of assets into the classroom.

Assess

Teachers can measure student understanding of the content and skills covered in the unit and provide actionable feedback to students.

- As you teach each topic, use **AP Classroom** to assign student **Topic Questions** as a way to continuously check student understanding and provide just in time feedback.
- At the end of each unit, use **AP Classroom** to assign students **Progress Checks**, as homework or an in-class task.
- Provide question-level feedback to students through answer rationales; provide unit- and skill-level formative feedback using **Reports**.
- Create additional practice opportunities using the **Question Bank** and assign them through **AP Classroom**.

About the AP Chemistry Course

The AP Chemistry course provides students with a college-level foundation to support future advanced coursework in chemistry. Students cultivate their understanding of chemistry through inquiry-based investigations, as they explore content such as:

- Atomic Structure and Properties
- Compound Structure and Properties
- Properties of Substances and Mixtures
- Chemical Reactions
- Kinetics
- Thermochemistry
- Equilibrium
- Acids and Bases
- Thermodynamics and Electrochemistry

College Course Equivalent

AP Chemistry is equivalent to a college-level general chemistry course.

Prerequisites

Students should have successfully completed an introductory high school chemistry course and Algebra II, or an equivalent course.

Laboratory Requirement

This course requires that 25 percent of instructional time be spent in hands-on laboratory work, with an emphasis on inquiry-based investigations that provide students with opportunities to demonstrate the foundational chemistry principles and apply the science practices. This includes a minimum of 16 hands-on labs (at least six of which are inquiry-based).

Inquiry-based laboratory experiences support the AP Chemistry course and AP Course Audit curricular requirements by providing opportunities for students to engage in the science practices as they design plans for experiments, make predictions, collect and analyze data, apply mathematical routines, develop explanations, and communicate about their work.

Colleges may require students to present their laboratory materials from AP science courses before granting college credit for laboratory work, so students should be encouraged to retain their laboratory notebooks, reports, and other materials.

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AP CHEMISTRY

Course Framework

Introduction

The AP Chemistry course outlined in this framework reflects what chemistry teachers, professors, and researchers have agreed is the main goal of a college-level general chemistry course: to help students develop a robust conceptual understanding of chemical principles that can be applied to future coursework and phenomena. The course is designed to enable students to view chemical phenomena through a variety of conceptual lenses, and at various levels: macroscopic, microscopic, sub-microscopic, and symbolic. Throughout the course, students learn to apply a variety of science practices, such as describing, interpreting, and analyzing models; designing experiments and analyzing data; creating representations of data and chemical systems; using mathematical routines to solve problems; and providing evidence and reasoning to justify a scientific claim.

To develop this robust understanding of the chemical world, the AP Chemistry course defines concepts, science practices, and understandings required by representative colleges and universities for granting college credit and placement. Students will practice reasoning skills by using chemical models to analyze, explain, and predict phenomena, and by supporting claims with scientific evidence from data, models, and theories. Students will develop inquiry and reasoning skills by designing and conducting inquiry-based laboratory investigations to answer scientific questions through observations, data collection, data analysis and interpretation, troubleshooting and procedural refinement, and error analysis.

This document is not a complete curriculum. Teachers create their own local curriculum by selecting, for each concept, content that enables students to explore the course learning objectives and meets state or local requirements. The result is a course that prepares students for college credit and placement.

Course Framework Components

Overview

This course framework provides a clear and detailed description of the course requirements necessary for student success. The framework specifies what students must know, be able to do, and understand to qualify for college credit and/or placement.

The course framework includes two essential components:

① **SCIENCE PRACTICES**

The science practices are central to the study and practice of chemistry. Students should develop and apply the described practices on a regular basis over the span of the course.

② **COURSE CONTENT**

The course content is organized into commonly taught units of study that provide a suggested sequence for the course and detail required content and conceptual understandings that colleges and universities typically expect students to be proficient in to qualify for college credit and/or placement.

1

AP CHEMISTRY

Science Practices

The table that follows presents the science practices that students should develop during the AP Chemistry course. These practices form the basis of many tasks on the AP Chemistry Exam.

The Unit Guides that follow embed and spiral these practices throughout the course, providing teachers with one way to integrate the practices into the course content with sufficient repetition to prepare students to apply those science practices on the AP Chemistry exam.

More detailed information about teaching the science practices can be found in the **Instructional Approaches** section of this publication.

AP CHEMISTRY

Science Practices

Practice 1

Models and Representations 1

Describe models and representations, including across scales.

Practice 2

Question and Method 2

Determine scientific questions and methods.

Practice 3

Representing Data and Phenomena 3

Create representations or models of chemical phenomena.

SKILLS

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

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

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

2.B Formulate a hypothesis or predict the results of an experiment.

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

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

2.E Identify or describe potential sources of experimental error.

2.F Explain how modifications to an experimental procedure will alter results.

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

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

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

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AP CHEMISTRY

Science Practices *(cont'd)*

Practice 4

Model Analysis 4

Analyze and interpret models and representations on a single scale or across multiple scales.

Practice 5

Mathematical Routines 5

Solve problems using mathematical relationships.

Practice 6

Argumentation 6

Develop an explanation or scientific argument.

SKILLS

4.A Predict and/or explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.

4.B Explain whether a model is consistent with chemical theories.

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

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

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

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

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

5.D Identify information presented graphically to solve a problem.

5.E Determine a balanced chemical equation for a given chemical phenomenon.

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.A Make a scientific claim.

6.B Support a claim with evidence from experimental data.

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

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

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

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

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

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AP CHEMISTRY

Course Content

The AP Chemistry course framework provides a clear and detailed description of the course requirements necessary for student success. The framework specifies what students must know, be able to do, and understand with a focus on core principles, theories, and processes of chemistry that prepare them for advanced chemistry coursework.

UNITS

The course content is organized into commonly taught units. The units have been arranged in a logical sequence frequently found in many college courses and textbooks.

The nine units in AP Chemistry, and their weighting on the multiple-choice section of the AP Exam, are listed on the following page.

Pacing recommendations at the unit level and on the Course at a Glance provide suggestions for how to teach the required course content and administer the Progress Checks. The suggested class periods are based on a schedule in which the class meets five days a week for 45 minutes each day. While these recommendations have been made to aid planning, teachers should adjust the pacing based on the needs of their students, alternate schedules (e.g., block scheduling), or their school's academic calendar.

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Units of Instruction	Exam Weighting
Unit 1: *Atomic Structure and Properties*	**7–9%**
Unit 2: *Compound Structure and Properties*	**7–9%**
Unit 3: *Properties of Substances and Mixtures*	**18–22%**
Unit 4: *Chemical Reactions*	**7–9%**
Unit 5: *Kinetics*	**7–9%**
Unit 6: *Thermochemistry*	**7–9%**
Unit 7: *Equilibrium*	**7–9%**
Unit 8: *Acids and Bases*	**11–15%**
Unit 9: *Thermodynamics and Electrochemistry*	**7–9%**

TOPICS

Each unit is broken down into teachable segments called topics. The topic pages (starting on p. 30) contain the required content for each topic.

Learning Objectives and Science Practices

In AP Chemistry, every exam question will be aligned to a learning objective and a skill. The learning objectives represent the content domain, while the skill articulates the science practice required to successfully complete the task. The six categories of science practices are described as discrete practices; they are, in fact, interrelated and should be applied throughout the course. For a given learning objective, teachers are encouraged to ask the following questions about a phenomenon to help students apply the science practices:

- How could the concepts be described verbally?
- What experiment could a student design, or what data would students analyze?
- How could students create or interpret graphs and other visual representations?
- How could students explain the phenomenon using theories or models?
- What quantitative problems could students solve?
- How could the course content be used as evidence to justify or support a claim about the behavior of a system, chemical phenomena, or outcome of an experiment?

Equations

Relevant equations are included in the Topic pages within this course framework and are labeled as “EQN:”. All of the equations in this course framework appear on the equation sheet provided to students while taking the AP Chemistry Exam. Additionally, variables used within this course framework follow the definitions given on the equation sheet. For a complete list of the equations available to students on the AP Chemistry Exam, please see the AP Chemistry Equations and Constants in Appendix 2.

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 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

Required Course Content

Each topic contains required Learning Objective and Essential Knowledge Statements that form the basis of the assessment on the AP Exam.

Assess

Assign the Progress Checks—either as homework or in class—for each unit. Each Progress Check contains formative multiple-choice and free-response questions. The feedback from the 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

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

Progress Check 1

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

- Short
- Short

UNIT 2 Compound Structure and Properties

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

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

Progress Check 2

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

- Long

continued on next page

UNIT 3 Properties of Substances and Mixtures

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

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

Progress Check 3

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

- Short
- Short

UNIT 4 Chemical Reactions

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

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

Progress Check 4

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

- Long

UNIT 5 Kinetics

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

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

Progress Check 5

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

- Short
- Long

continued on next page

Return to Table of Contents

UNIT 6 Thermochemistry

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

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

Progress Check 6

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

- Short
- Short

UNIT 7 Equilibrium

~13–15 Class Periods | **7–9%** AP Exam Weighting

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

Progress Check 7

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

- Short
- Long

UNIT 8 Acids and Bases

~14–16 Class Periods | **11–15%** AP Exam Weighting

5	**8.1**	Introduction to Acids and Bases
5	**8.2**	pH and pOH of Strong Acids and Bases
5	**8.3**	Weak Acid and Base Equilibria
5	**8.4**	Acid-Base Reactions and Buffers
5	**8.5**	Acid-Base Titrations
6	**8.6**	Molecular Structure of Acids and Bases
2	**8.7**	pH and pK_a
6	**8.8**	Properties of Buffers
5	**8.9**	Henderson-Hasselbalch Equation
6	**8.10**	Buffer Capacity
2	**8.11**	pH and Solubility

Progress Check 8

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

- Long

continued on next page

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UNIT 9

Thermodynamics and Electrochemistry

~10–13 Class Periods

7–9% AP Exam Weighting

6	**9.1**	Introduction to Entropy
5	**9.2**	Absolute Entropy and Entropy Change
6	**9.3**	Gibbs Free Energy and Thermodynamic Favorability
6	**9.4**	Thermodynamic and Kinetic Control
6	**9.5**	Free Energy and Equilibrium
4	**9.6**	Free Energy of Dissolution
4	**9.7**	Coupled Reactions
2	**9.8**	Galvanic (Voltaic) and Electrolytic Cells
5	**9.9**	Cell Potential and Free Energy
6	**9.10**	Cell Potential Under Nonstandard Conditions
5	**9.11**	Electrolysis and Faraday's Law

Progress Check 9

Multiple-choice: ~30 questions

Free-response: 2 questions

- Short
- Long

AP CHEMISTRY

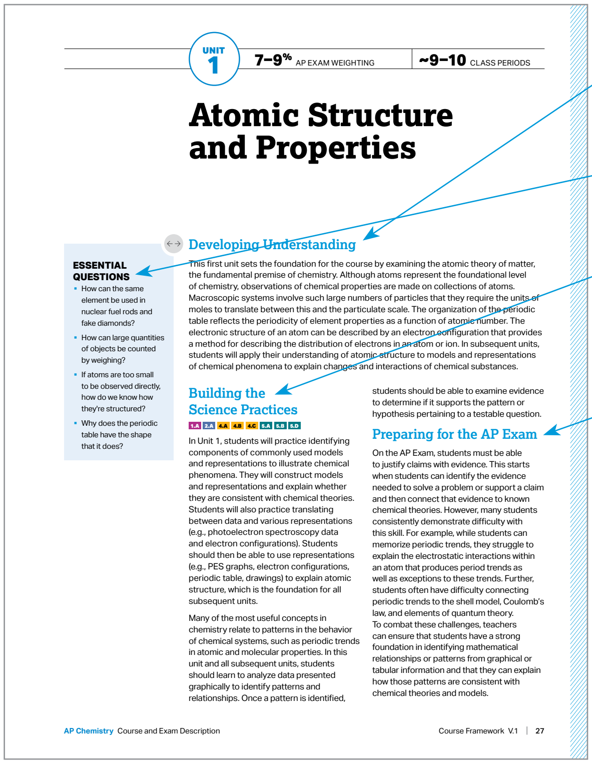
Unit Guides

Introduction

Designed with input from the community of AP Chemistry educators, the Unit Guides offer teachers helpful guidance in building students' skills and content knowledge. The suggested sequence was identified through a thorough analysis of the syllabi of highly effective AP teachers and the organization of typical college textbooks.

This unit structure respects new AP teachers' time by providing one possible sequence they can adopt or modify rather than having to build from scratch. An additional benefit is that these units enable the AP Program to provide interested teachers with formative assessments—the Progress Checks—that they can assign their students at the end of each unit to gauge progress toward success on the AP Exam. However, experienced AP teachers who are satisfied with their current course organization and exam results should feel no pressure to adopt these units, which comprise an optional sequence for this course.

Using the Unit Guides



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

Atomic Structure and Properties

ESSENTIAL QUESTIONS

- How can the same element be used in nuclear fuel rods and fake diamonds?
- How can large quantities of objects be counted by weighing?
- If atoms are too small to be observed directly, how do we know how they're structured?
- Why does the periodic table have the shape that it does?

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 of particles that they require the units of moles to translate between this and the particulate scale. The organization of the periodic table reflects the periodicity of element properties as a function of 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 to 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.

AP Chemistry Course and Exam Description Course Framework V.1 | 27

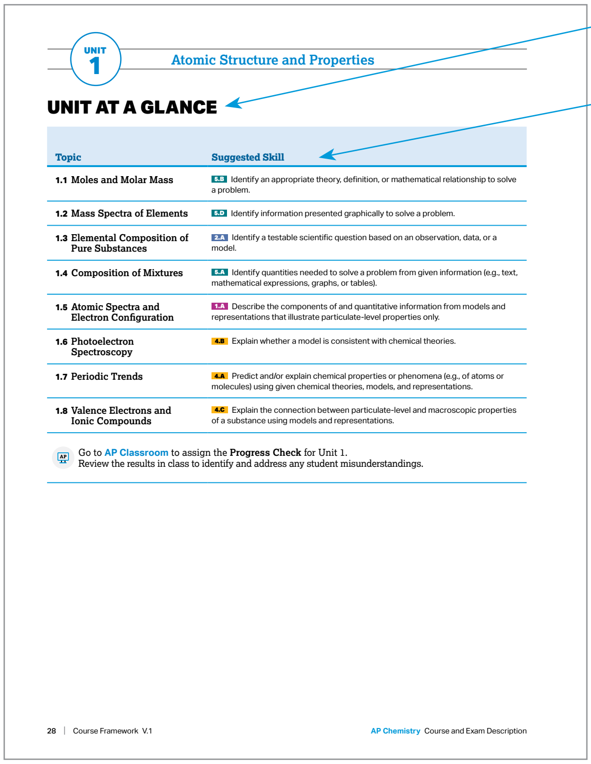
UNIT OPENERS

Developing Understanding provides an overview that contextualizes and situates the key content of the unit within the scope of the course.

The **essential questions** are thought-provoking questions that motivate students and inspire inquiry.

Building the Science Practices describes specific skills within the practices that are appropriate to focus on in that unit. Certain skills have been noted to indicate areas of emphasis for that unit.

Preparing for the AP Exam provides helpful tips and common student misunderstandings identified from prior exam data.



UNIT 1 Atomic Structure and Properties

UNIT AT A GLANCE

Topic	Suggested Skill
1.1 Moles and Molar Mass	5.B Identify an appropriate theory, definition, or mathematical relationship to solve a problem.
1.2 Mass Spectra of Elements	5.D Identify information presented graphically to solve a problem.
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).
1.5 Atomic Spectra 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.
1.7 Periodic Trends	4.A Predict and/or 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.

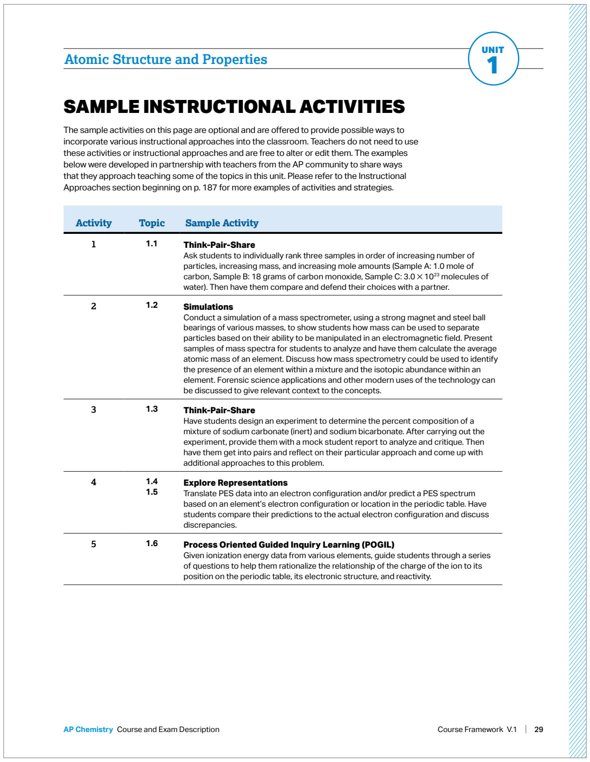
Go to **AP Classroom** to assign the **Progress Check** for Unit 1.
Review the results in class to identify and address any student misunderstandings.

28 | Course Framework V.1 AP Chemistry Course and Exam Description

The **Unit at a Glance table** shows the topics and suggested skills.

The **suggested skill** for each topic shows one way to link the content in that topic to a specific AP Chemistry skill. The individual skills have been thoughtfully chosen in a way that allows teachers to scaffold the practices throughout the course. The questions on the Progress Checks are based on this pairing. However, AP Exam questions can pair the content with any of the skills.

Using the Unit Guides



Atomic Structure and Properties

UNIT 1

SAMPLE INSTRUCTIONAL ACTIVITIES

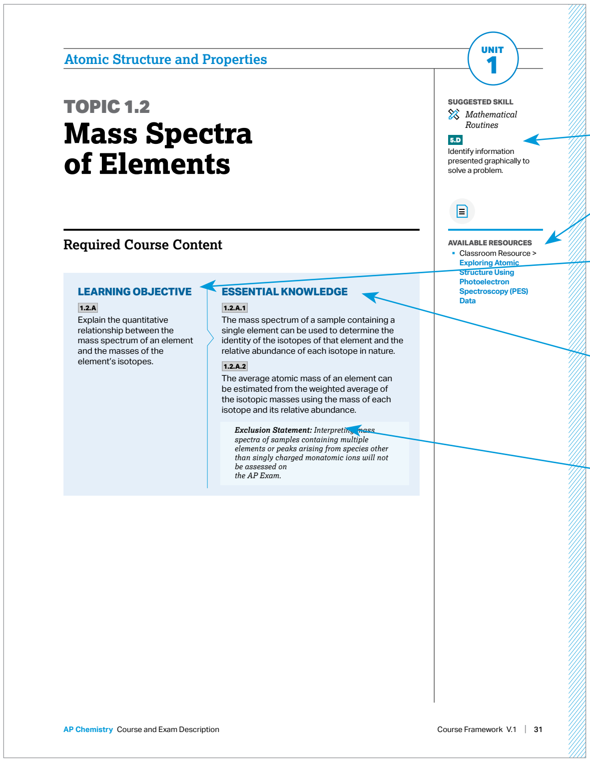
The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in 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. 187 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.

AP Chemistry Course and Exam Description Course Framework V.1 | 29

The **Sample Instructional Activities** page includes optional activities that can help tie together the content and skill of a particular topic.

TOPIC PAGES



Atomic Structure and Properties

UNIT 1

TOPIC 1.2

Mass Spectra of Elements

Required Course Content

LEARNING OBJECTIVE

1.2.A

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

ESSENTIAL KNOWLEDGE

1.2.A.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.

1.2.A.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.

Exclusion Statement: *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

AP Chemistry Course and Exam Description Course Framework V.1 | 31

The **suggested skill** offers a possible skill to pair with the topic.

Where possible, **available resources** are provided that might help teachers address a particular topic.

Learning objectives define what a student needs to be able to do with content knowledge in order to progress toward the enduring understandings.

Essential knowledge statements define the required content knowledge associated with each learning objective assessed on the AP Exam.

Exclusion statements define content or specific details about content that will not be assessed on the AP Chemistry Exam. However, such content may be provided as background or additional information for the concepts and science practices being assessed.

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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 **Progress Check** for this unit.

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

Progress Check 1

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

- Short
- Short

UNIT 1

7–9% AP EXAM WEIGHTING

~9–10 CLASS PERIODS

Atomic Structure and Properties

ESSENTIAL QUESTIONS

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

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

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UNIT AT A GLANCE

Topic	Suggested Skill
1.1 Moles and Molar Mass	**5.B** Identify an appropriate theory, definition, or mathematical relationship to solve a problem.
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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).
1.5 Atomic Spectra 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.
1.7 Periodic Trends	**4.A** Predict and/or explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.
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Go to **AP Classroom** to assign the **Progress Check** for Unit 1.
Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

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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.

TOPIC 1.1

Moles and Molar Mass

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 3: What Makes Hard Water Hard?**
- Classroom Resource > **Guided Inquiry Activities for the Classroom: Lesson 1**

Required Course Content

LEARNING OBJECTIVE

1.1.A

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

ESSENTIAL KNOWLEDGE

1.1.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.

1.1.A.2

Avogadro's number ($N_A = 6.022 \times 10^{23}\ \text{mol}^{-1}$) 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.

1.1.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: $n = m/\boldsymbol{M}$

TOPIC 1.2

Mass Spectra of Elements

Required Course Content

LEARNING OBJECTIVE

1.2.A

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

ESSENTIAL KNOWLEDGE

1.2.A.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.

1.2.A.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.

Exclusion Statement: *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?**
- The Exam > **2023 Chief Reader Report**

TOPIC 1.3

Elemental Composition of Pure Substances

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.3.A Explain the quantitative relationship between the elemental composition by mass and the empirical formula of a pure substance.	**1.3.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. **1.3.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. **1.3.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

SUGGESTED SKILL

Mathematical Routines

5.A

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

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.4.A Explain the quantitative relationship between the elemental composition by mass and the composition of substances in a mixture.	**1.4.A.1** Pure substances contain atoms, molecules, or formula units of a single type. Mixtures contain atoms, molecules, or formula units of two or more types, whose relative proportions can vary. **1.4.A.2** Elemental analysis can be used to determine the relative numbers of atoms in a substance and to determine its purity.

SUGGESTED SKILL

Models and Representations

1.A

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

TOPIC 1.5

Atomic Structure and Electron Configuration

Required Course Content

LEARNING OBJECTIVE

1.5.A

Represent the ground-state electron configuration of an atom of an element or its ions using the Aufbau principle.

ESSENTIAL KNOWLEDGE

1.5.A.1

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

1.5.A.2

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

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

1.5.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 ground-state 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.

> ***Exclusion Statement:*** *The assignment of quantum numbers to electrons in subshells of an atom will not be assessed on the AP Exam.*

continued on next page

LEARNING OBJECTIVE

1.5.A

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

ESSENTIAL KNOWLEDGE

1.5.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**
- The Exam > **2021 Chief Reader Report**

TOPIC 1.6

Photoelectron Spectroscopy

Required Course Content

LEARNING OBJECTIVE

1.6.A

Explain the relationship between the photoelectron spectrum of an atom or ion and:

i. The ground-state electron configuration of the species.

ii. The interactions between the electrons and the nucleus.

ESSENTIAL KNOWLEDGE

1.6.A.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 relative 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

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

AVAILABLE RESOURCES

- The Exam > **2021 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE

1.7.A

Explain the relationship between trends in atomic properties of elements and electronic structure and periodicity.

ESSENTIAL KNOWLEDGE

1.7.A.1

The organization of the periodic table is based on patterns of recurring properties of the elements, which are explained by patterns of ground-state electron configurations and the presence of completely or partially filled shells (and subshells) of electrons in atoms.

> ***Exclusion Statement:*** *Writing the electron configuration of elements that are exceptions to the aufbau principle will not be assessed on the AP Exam.*

1.7.A.2

Trends in atomic properties within the periodic table (periodicity) can be predicted by the position of the element on the periodic table and qualitatively understood using Coulomb's law, the shell model, and the concepts of shielding and effective nuclear charge. These properties include:

i. Ionization energy

ii. Atomic and ionic radii

iii. Electron affinity

iv. Electronegativity.

1.7.A.3

The periodicity (in 1.7.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

LEARNING OBJECTIVE

1.8.A

Explain the relationship between trends in the reactivity of elements and periodicity.

ESSENTIAL KNOWLEDGE

1.8.A.1

The likelihood that two elements will form a chemical bond is determined by the interactions between the valence electrons and nuclei of elements.

1.8.A.2

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

1.8.A.3

Typical charges of atoms in ionic compounds are governed by the number of valence electrons and predicted by their location on the periodic table.

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AP CHEMISTRY

UNIT 2

Compound Structure and Properties

7–9%
AP EXAM WEIGHTING

~12–13
CLASS PERIODS

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

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

Progress Check 2

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

- Long

UNIT
2

7–9% AP EXAM WEIGHTING

~12–13 CLASS PERIODS

Compound Structure and Properties

ESSENTIAL QUESTIONS

- How are molecular compounds arranged?
- Why are some bonds easier to break than others?
- In what ways does a diagram drawn on paper accurately reflect the structure of a molecule? In what ways does it not accurately reflect the structure?

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 provide 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

Topic	Suggested Skill
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.
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 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 **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. 187 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

LEARNING OBJECTIVE

2.1.A

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

ESSENTIAL KNOWLEDGE

2.1.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.

2.1.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.

2.1.A.3

Valence electrons shared between atoms of unequal electronegativity constitute a polar covalent bond.

i. The atom with a higher electronegativity will develop a partial negative charge relative to the other atom in the bond.

ii. In single bonds, greater differences in electronegativity lead to greater bond dipoles.

iii. All polar bonds have some ionic character, and the difference between ionic and covalent bonding is not distinct but rather a continuum.

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LEARNING OBJECTIVE

2.1.A

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

ESSENTIAL KNOWLEDGE

2.1.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.

2.1.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.

TOPIC 2.2
Intramolecular Force and Potential Energy

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 Resource > **Ending Misconceptions About the Energy of Chemical Bonds**
- The Exam > **2023 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE

2.2.A

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

ESSENTIAL KNOWLEDGE

2.2.A.1

A graph of potential energy versus the distance between atoms (internuclear distance) 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).

2.2.A.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.

2.2.A.3

Coulomb's law can be used to understand the strength of interactions between cations and anions.

1. Because the interaction strength is proportional to the charge on each ion, larger charges lead to stronger interactions.
2. 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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.3.A Represent an ionic solid with a particulate model that is consistent with Coulomb's law and the properties of the constituent ions.	**2.3.A.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. ***Exclusion Statement:*** *Knowledge of specific crystal structures is not essential to an understanding of the learning objective and will not be assessed on the AP Exam.*

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.4.A Represent a metallic solid and/or alloy using a model to show essential characteristics of the structure and interactions present in the substance.	**2.4.A.1** Metallic bonding can be represented as an array of positive metal ions surrounded by delocalized valence electrons (i.e., a “sea of electrons”). **2.4.A.2** Interstitial alloys form between atoms of significantly 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). **2.4.A.3** Substitutional alloys form between atoms of comparable radius, where one atom substitutes for the other in the lattice. (e.g., in certain brass alloys, other elements, usually zinc, substitute for copper.)

TOPIC 2.5

Lewis Diagrams

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.5.A Represent a molecule with a Lewis diagram.	**2.5.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**
- The Exam > **2018 Chief Reader Report**

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

LEARNING OBJECTIVE

2.6.A

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

2.6.A.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.

2.6.A.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.

2.6.A.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 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

LEARNING OBJECTIVE

2.7.A

Based on the relationship between Lewis diagrams, VSEPR theory, bond orders, and bond polarities:

i. Explain structural properties of molecules.
ii. Explain electron properties of molecules.

ESSENTIAL KNOWLEDGE

2.7.A.1

VSEPR theory uses the Coulombic repulsion between electrons as a basis for predicting the arrangement of electron pairs around a central atom.

2.7.A.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:

i. Molecular geometry (linear, trigonal planar, tetrahedral, trigonal pyramidal, bent, trigonal bipyramidal, seesaw, T-shaped, octahedral, square pyramidal, square planar)
ii. Bond angles
iii. Relative bond energies based on bond order
iv. Relative bond lengths (multiple bonds, effects of atomic radius)
v. Presence of a dipole moment
vi. Hybridization of valence orbitals for atoms within a molecule or polyatomic ion

2.7.A.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°.

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LEARNING OBJECTIVE

2.7.A

Based on the relationship between Lewis diagrams, VSEPR theory, bond orders, and bond polarities:

i. Explain structural properties of molecules.

ii. Explain electron properties of molecules.

ESSENTIAL KNOWLEDGE

Exclusion Statement: *An understanding of the derivation and depiction of hybrid orbitals will not be assessed on the AP Exam. 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.*

Exclusion Statement: *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.*

2.7.A.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 geometric isomers.

Exclusion Statement: *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.*

AP CHEMISTRY

UNIT 3

Properties of Substances and Mixtures

18–22%
AP EXAM WEIGHTING

~14–15
CLASS PERIODS

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

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

Progress Check 3

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

- Short
- Short

UNIT
3

18–22% AP EXAM WEIGHTING

~14–15 CLASS PERIODS

Properties of Substances and Mixtures

ESSENTIAL QUESTIONS

- How do interactions between particles influence the properties of pure substances and mixtures?
- Why does the smell of perfume only last for a short time?
- Why can you swim in water, but you can't walk through a wall?
- How does the spacing and motion of particles relate to a substance's state of matter and the properties of gases?
- 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 are required to compare the physical properties of substances and relate them to the attractive forces between particles. 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 points, 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 AT A GLANCE

Topic	Suggested Skill
3.1 Intermolecular and Interparticle 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.
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).
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 Predict and/or 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.
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	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.
3.11 Spectroscopy and the Electromagnetic Spectrum	4.A Predict and/or explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.
3.12 Properties of Photons	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 **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. 187 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.

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**

TOPIC 3.1

Intermolecular and Interparticle Forces

Required Course Content

LEARNING OBJECTIVE

3.1.A

Explain the relationship between the chemical structures of molecules and the relative strength of their intermolecular forces when:

i. The molecules are of the same chemical species.

ii. The molecules are of two different chemical species.

ESSENTIAL KNOWLEDGE

3.1.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.

i. Dispersion forces increase with increasing contact area between molecules and with increasing polarizability of the molecules.

ii. 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.

iii. The term “London dispersion forces” should not be used synonymously with the term “van der Waals forces.”

3.1.A.2

The dipole moment of a polar molecule leads to additional interactions with other chemical species.

i. 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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LEARNING OBJECTIVE

3.1.A

Explain the relationship between the chemical structures of molecules and the relative strength of their intermolecular forces when:

i. The molecules are of the same chemical species.

ii. The molecules are of two different chemical species.

ESSENTIAL KNOWLEDGE

ii. 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.

iii. Ion-dipole forces of attraction are present between ions and polar molecules. These tend to be stronger than dipole-dipole forces.

3.1.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.

3.1.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.

3.1.A.5

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

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?**

TOPIC 3.2

Properties of Solids

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.2.A Explain the relationship among the macroscopic properties of a substance, the particulate-level structure of the substance, and the interactions between these particles.	**3.2.A.1** Many properties of liquids and solids are determined by the strengths and types of intermolecular forces present. Because intermolecular interactions are overcome completely 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. **3.2.A.2** Particulate-level representations, showing multiple interacting chemical species, are a useful means to communicate or understand how intermolecular interactions help to establish macroscopic properties. **3.2.A.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 (i.e., in a molten state) or dissolved in water or another solvent.

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LEARNING OBJECTIVE

3.2.A

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

3.2.A.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 and metalloids: elemental (e.g., diamond, graphite) or binary compounds (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.

3.2.A.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.

3.2.A.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.

3.2.A.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.

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**

TOPIC 3.3

Solids, Liquids, and Gases

Required Course Content

LEARNING OBJECTIVE

3.3.A

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

ESSENTIAL KNOWLEDGE

3.3.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.

3.3.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.

3.3.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.

3.3.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.

Exclusion Statement: *Understanding/interpreting phase diagrams will not be assessed on the AP Exam.*

TOPIC 3.4

Ideal Gas Law

SUGGESTED SKILL

Mathematical Routines

5.C

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

AVAILABLE RESOURCES

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

Required Course Content

LEARNING OBJECTIVE

3.4.A

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

ESSENTIAL KNOWLEDGE

3.4.A.1

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

EQN: $PV = nRT$.

3.4.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 partial pressure of a gas within the mixture is proportional to its mole fraction (X), and 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: $P_{total} = P_A + P_B + P_C + \ldots$

3.4.A.3

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

SUGGESTED SKILL

Model Analysis

4.A

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

TOPIC 3.5

Kinetic Molecular Theory

Required Course Content

LEARNING OBJECTIVE

3.5.A

Explain the relationship between the motion of particles and the macroscopic properties of gases with:

i. The kinetic molecular theory (KMT).

ii. A particulate model.

iii. A graphical representation.

ESSENTIAL KNOWLEDGE

3.5.A.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.

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

3.5.A.3

The Kelvin temperature of a sample of matter is proportional to the average kinetic energy of the particles in the sample.

3.5.A.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

- The Exam > **2019 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.6.A Explain the relationship among non-ideal behaviors of gases, interparticle forces, and/or volumes.	**3.6.A.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

LEARNING OBJECTIVE

3.7.A

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

ESSENTIAL KNOWLEDGE

3.7.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.

3.7.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).

AVAILABLE RESOURCES

- The Exam > **2021 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE

3.8.A

Using particulate models for mixtures:

i. Represent interactions between components.

ii. Represent concentrations of components.

ESSENTIAL KNOWLEDGE

3.8.A.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/or drawings that show interactions among the components.

> ***Exclusion Statement:*** *Colligative properties will not be assessed on the AP Exam.*
>
> ***Exclusion Statement:*** *Calculations of molality, percent by mass, and percent by volume for solutions 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

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.9.A Explain the results of a separation experiment based on intermolecular interactions.	**3.9.A.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. i. 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. The resulting chromatogram can be used to infer the relative polarities of components in a mixture. ii. 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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.10.A Explain the relationship between the solubility of ionic and molecular compounds in aqueous and nonaqueous solvents, and the intermolecular interactions between particles.	**3.10.A.1** Substances with similar intermolecular interactions tend to be miscible or soluble in one another.

SUGGESTED SKILL

Model Analysis

4.A

Predict and/or 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

LEARNING OBJECTIVE

3.11.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

3.11.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:

i. Microwave radiation is associated with transitions in molecular rotational levels.

ii. Infrared radiation is associated with transitions in molecular vibrational levels.

iii. Ultraviolet/visible radiation is associated with transitions in electronic energy levels.

TOPIC 3.12

Properties of Photons

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

LEARNING OBJECTIVE

3.12.A

Explain the properties of an absorbed or emitted photon in relationship to an electronic transition in an atom or molecule.

ESSENTIAL KNOWLEDGE

3.12.A.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.

3.12.A.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:

EQN: $E = h\nu$.

SUGGESTED SKILL

Question and Method

2.E

Identify or describe potential sources of experimental error.

AVAILABLE RESOURCES

- The Exam > **2021 Chief Reader Report**

TOPIC 3.13

Beer-Lambert Law

Required Course Content

LEARNING OBJECTIVE

3.13.A

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

3.13.A.1

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

EQN: $A = \varepsilon bc$.

The molar absorptivity, ε, describes how intensely a chemical species absorbs light of a specific wavelength. The path length, b, and concentration, c, are proportional to the number of light-absorbing particles in the light path.

3.13.A.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. The spectrophotometer is typically set to the wavelength of maximum absorbance (optimum wavelength) for the species being analyzed to ensure the maximum sensitivity of measurement.

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 **Progress Check** for this unit.

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

Progress Check 4

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

- Long

UNIT
4

7–9% AP EXAM WEIGHTING

~14–15 CLASS PERIODS

Chemical Reactions

ESSENTIAL QUESTIONS

- What makes fireworks explode?
- In what ways can a chemical change be described and documented?
- How can you predict that a chemical reaction will generate enough product?

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 encounter difficulty 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

Topic	Suggested Skill
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.
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.
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 **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. 187 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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
4.1.A Identify evidence of chemical and physical changes in matter.	**4.1.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. **4.1.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

LEARNING OBJECTIVE

4.2.A

Represent changes in matter with a balanced chemical or net ionic equation:

i. For physical changes.

ii. For given information about the identity of the reactants and/or product.

iii. For ions in a given chemical reaction.

ESSENTIAL KNOWLEDGE

4.2.A.1

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

4.2.A.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 and charge are conserved in chemical reactions.

4.2.A.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 H_2O_2 in a Drugstore Bottle of Hydrogen Peroxide?**
- The Exam > **2023 Chief Reader Report**

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**
- The Exam > **2022 Chief Reader Report**

TOPIC 4.3

Representations of Reactions

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
4.3.A Represent a given chemical reaction or physical process with a consistent particulate model.	**4.3.A.1** Balanced chemical equations in their various forms can be translated into symbolic particulate representations.

TOPIC 4.4

Physical and Chemical Changes

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
4.4.A Explain the relationship between macroscopic characteristics and bond interactions for: i. Chemical processes. ii. Physical processes.	**4.4.A.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. **4.4.A.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

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?**

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

LEARNING OBJECTIVE

4.5.A

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

ESSENTIAL KNOWLEDGE

4.5.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.

4.5.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.

4.5.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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
4.6.A Identify the equivalence point in a titration based on the amounts of the titrant and analyte, assuming the titration reaction goes to completion.	**4.6.A.1** Titrations may be used to determine the amount 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?**
- The Exam > **2018 Chief Reader Report**

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

LEARNING OBJECTIVE

4.7.A

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

ESSENTIAL KNOWLEDGE

4.7.A.1

Acid-base reactions involve transfer of one or more protons (H^+ ions) between chemical species.

4.7.A.2

Oxidation-reduction (redox) 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.

4.7.A.3

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

> ***Exclusion Statement:*** *The meaning of the terms "reducing agent" and "oxidizing agent" will not be assessed on the AP Exam.*

4.7.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.

continued on next page

LEARNING OBJECTIVE

4.7.A

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

ESSENTIAL KNOWLEDGE

4.7.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.

Exclusion Statement: *Rote memorization of "solubility rules" other than those implied in 4.7.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

LEARNING OBJECTIVE

4.8.A

Identify species as Brønsted-Lowry acids, bases, and/or conjugate acid-base pairs, based on proton-transfer involving those species.

ESSENTIAL KNOWLEDGE

4.8.A.1

By definition, a Brønsted-Lowry acid is a proton donor and a Brønsted-Lowry base is a proton acceptor.

4.8.A.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.

4.8.A.3

When an acid or base ionizes in water, the conjugate acid-base pairs can be identified and their relative strengths compared.

> ***Exclusion Statement:*** *Lewis acid-base concepts will not be assessed on the AP Exam. The emphasis in AP Chemistry is on reactions in aqueous solution.*

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
4.9.A Represent a balanced redox reaction equation using half-reactions.	**4.9.A.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 **Progress Check** for this unit.

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

Progress Check 5

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

- Short
- Long

UNIT
5

7–9% AP EXAM WEIGHTING

~13–14 CLASS PERIODS

Kinetics

ESSENTIAL QUESTIONS

- Why are some reactions faster than other reactions?
- Why are some medications taken every 8 hours and others once a day?
- Why is food stored in a refrigerator, but bread dough is kept in a warm place to rise?
- How can the speed of a reaction be controlled by understanding the collisions that occur on the particle level?

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, teachers can help them analyze the graphs to determine the order of a reaction.

UNIT AT A GLANCE

Topic	Suggested Skill
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.
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).
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).
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 **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. 187 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?**
- The Exam > **2023 Chief Reader Report**

TOPIC 5.1

Reaction Rates

Required Course Content

LEARNING OBJECTIVE

5.1.A

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

ESSENTIAL KNOWLEDGE

5.1.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.

5.1.A.2

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

5.1.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

Required Course Content

LEARNING OBJECTIVE

5.2.A

Represent experimental data with a consistent rate law expression.

ESSENTIAL KNOWLEDGE

5.2.A.1

Experimental methods can be used to monitor the amounts of reactants and/or products of a reaction over time and to determine the rate of the reaction.

5.2.A.2

The rate law expresses the rate of a reaction as proportional to the concentration of each reactant raised to a power.

5.2.A.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.

5.2.A.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.

5.2.A.5

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

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**

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?**
- The Exam > **2022 Chief Reader Report**

TOPIC 5.3

Concentration Changes Over Time

Required Course Content

LEARNING OBJECTIVE

5.3.A

Identify the rate law expression of a chemical reaction using data that show how the concentrations of reaction species change over time.

ESSENTIAL KNOWLEDGE

5.3.A.1

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

5.3.A.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.

5.3.A.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.

5.3.A.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:

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

First order:

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

Second order:

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

continued on next page

LEARNING OBJECTIVE

5.3.A

Identify the rate law expression of a chemical reaction using data that show how the concentrations of reaction species change over time.

ESSENTIAL KNOWLEDGE

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

5.3.A.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.

TOPIC 5.4

Elementary Reactions

Required Course Content

LEARNING OBJECTIVE

5.4.A

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

ESSENTIAL KNOWLEDGE

5.4.A.1

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

5.4.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.

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.5.A Explain the relationship between the rate of an elementary reaction and the frequency, energy, and orientation of particle collisions.	**5.5.A.1** For an elementary reaction to successfully produce products, reactants must successfully collide to initiate bond-breaking and bond-making events. **5.5.A.2** In most reactions, only a small fraction of the collisions leads to a reaction. Successful collisions have both sufficient energy to overcome the activation energy requirements and orientations that allow the bonds to rearrange in the required manner. **5.5.A.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

LEARNING OBJECTIVE

5.6.A

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

ESSENTIAL KNOWLEDGE

5.6.A.1

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

5.6.A.2

The reaction coordinate is the axis along which the complex set of motions involved in rearranging reactants to form products can be plotted.

5.6.A.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.

5.6.A.4

The rate of an elementary reaction is temperature dependent because the proportion of particle collisions that are energetic enough to reach the transition state varies with temperature. 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.

Exclusion Statement: *Calculations involving the Arrhenius equation will not be assessed on the AP Exam.*

TOPIC 5.7

Introduction to Reaction Mechanisms

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.

Required Course Content

LEARNING OBJECTIVE

5.7.A

Identify the components of a reaction mechanism.

ESSENTIAL KNOWLEDGE

5.7.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.

5.7.A.2

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

5.7.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.

5.7.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.

Exclusion Statement: *Collection of data pertaining to detection of a reaction intermediate will not be assessed on the AP Exam.*

SUGGESTED SKILL

Mathematical Routines

5.B

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

AVAILABLE RESOURCES

- The Exam > **2022 Chief Reader Report**

TOPIC 5.8

Reaction Mechanism and Rate Law

Required Course Content

LEARNING OBJECTIVE

5.8.A

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

ESSENTIAL KNOWLEDGE

5.8.A.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).

Exclusion Statement: *Collection of data pertaining to detection of a reaction intermediate will not be assessed on the AP Exam.*

TOPIC 5.9

Pre-Equilibrium Approximation

Required Course Content

LEARNING OBJECTIVE

5.9.A

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

ESSENTIAL KNOWLEDGE

5.9.A.1

If the first elementary reaction is not rate limiting, approximations (such as pre-equilibrium) must be made to determine a rate law expression.

SUGGESTED SKILL

Mathematical Routines

5.B

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

AVAILABLE RESOURCES

- The Exam > **2019 Chief Reader Report**

SUGGESTED SKILL

Representing Data and Phenomena

3.B

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

TOPIC 5.10

Multistep Reaction Energy Profile

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.10.A Represent the activation energy and overall energy change in a multistep reaction with a reaction energy profile.	**5.10.A.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

SUGGESTED SKILL

Argumentation

6.E

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

AVAILABLE RESOURCES

- The Exam > **2021 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE

5.11.A

Explain the relationship between the effect of a catalyst on a reaction and changes in the reaction mechanism.

ESSENTIAL KNOWLEDGE

5.11.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.

5.11.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.

5.11.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.

5.11.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.

5.11.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

Thermochemistry

7–9%
AP EXAM WEIGHTING

~10–11
CLASS PERIODS

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

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

Progress Check 6

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

- Short
- Short

UNIT 6

7–9% AP EXAM WEIGHTING

~10–11 CLASS PERIODS

Thermochemistry

ESSENTIAL QUESTIONS

- Why is energy released when liquid water becomes an ice cube?
- Why does your skin feel cold when water evaporates off of it?
- How does a thermal energy transfer affect temperature, states of matter, and chemical bonds?
- How can energy changes be tracked and measured when energy can't be seen?
- Why do combustion reactions that form carbon dioxide release 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. Thermochemistry 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

Topic	Suggested Skill
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).
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 **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. 187 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.

TOPIC 6.1

Endothermic and Exothermic Processes

Required Course Content

LEARNING OBJECTIVE

6.1.A

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

ESSENTIAL KNOWLEDGE

6.1.A.1

Temperature changes in a system indicate energy changes.

6.1.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.

6.1.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.

6.1.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

Required Course Content

LEARNING OBJECTIVE

6.2.A

Represent a chemical or physical transformation with an energy diagram.

ESSENTIAL KNOWLEDGE

6.2.A.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

Representing Data and Phenomena

3.A

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

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.3.A Explain the relationship between the transfer of thermal energy and molecular collisions.	**6.3.A.1** The particles in a warmer body have a greater average kinetic energy than those in a cooler body. **6.3.A.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.” **6.3.A.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

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?**
- The Exam > **2021 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE

6.4.A

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

6.4.A.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.

6.4.A.2

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

6.4.A.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.

6.4.A.4

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

6.4.A.5

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

continued on next page

LEARNING OBJECTIVE

6.4.A

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

6.4.A.6

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

6.4.A.7

In calorimetry experiments involving dissolution, temperature changes of the mixture within the calorimeter can be used to determine the direction of energy flow. If the temperature of the mixture increases, thermal energy is released by the dissolution process (exothermic). If the temperature of the mixture decreases, thermal energy is absorbed by the dissolution process (endothermic).

TOPIC 6.5

Energy of Phase Changes

Required Course Content

LEARNING OBJECTIVE

6.5.A

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

6.5.A.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.

6.5.A.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 enthalpy of condensation of a substance is equal to the negative of its molar enthalpy of vaporization. Similarly, the molar enthalpy of fusion can be used to calculate the energy absorbed when melting a substance and the energy released when freezing a substance.

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?**
- The Exam > **2022 Chief Reader Report**

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?**
- The Exam > **2021 Chief Reader Report**

TOPIC 6.6

Introduction to Enthalpy of Reaction

Required Course Content

LEARNING OBJECTIVE

6.6.A

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

6.6.A.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.

6.6.A.2

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 as the reactants convert to products in an exothermic reaction. Thermal energy is transferred from the surroundings as the reactants convert to products in an endothermic reaction.

6.6.A.3

The chemical potential energy of the products of a reaction is different from that of the reactants because of the breaking and forming of bonds. The energy difference results in a change in the kinetic energy of the particles, which manifests as a temperature change.

Exclusion Statement: *The technical distinctions between enthalpy and internal energy will not be assessed on the AP Exam. Most reactions studied at the AP level are carried out at constant pressure, where the enthalpy change of the process is equal to the heat (and by extension, the energy) of reaction.*

TOPIC 6.7

Bond Enthalpies

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

LEARNING OBJECTIVE

6.7.A

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

ESSENTIAL KNOWLEDGE

6.7.A.1

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

6.7.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).

TOPIC 6.8

Enthalpy of Formation

Required Course Content

LEARNING OBJECTIVE

6.8.A

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

ESSENTIAL KNOWLEDGE

6.8.A.1

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

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

TOPIC 6.9

Hess's Law

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.9.A Represent a chemical or physical process as a sequence of steps.	**6.9.A.1** Many processes can be broken down into a series of steps. Each step in the series has its own energy change.
6.9.B Explain the relationship between the enthalpy of a chemical or physical process and the sum of the enthalpies of the individual steps.	**6.9.B.1** Because total energy is conserved (first law of thermodynamics), and each individual reaction in a sequence transfers thermal energy to or from the surroundings, the net thermal energy transferred in the sequence will be equal to the sum of the thermal energy transfers in each of the steps. These thermal energy transfers are the result of potential energy changes among the species in the reaction sequence; thus, at constant pressure, the enthalpy change of the overall process is equal to the sum of the enthalpy changes of the individual steps. **6.9.B.2** The following are essential principles of Hess's law: i. When a reaction is reversed, the enthalpy change stays constant in magnitude but becomes reversed in mathematical sign. ii. When a reaction is multiplied by a factor *c*, the enthalpy change is multiplied by the same factor *c*. iii. 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 change of the overall reaction. ***Exclusion Statement:*** *The concept of state functions will not be assessed on the AP Exam.*

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

- The Exam > **2023 Chief Reader Report**

AP CHEMISTRY

UNIT 7

Equilibrium

7–9%
AP EXAM WEIGHTING

~13–15
CLASS PERIODS

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

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

Progress Check 7

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

- Short
- Long

UNIT
7

7–9% AP EXAM WEIGHTING

~13–15 CLASS PERIODS

Equilibrium

ESSENTIAL QUESTIONS

- How are the rates of forward and reverse reactions related to the direction that a reversible reaction proceeds?
- How can the composition of a mixture at equilibrium be predicted?
- How can an equilibrium system be manipulated to maximize product yield?
- Why do paramedics administer pure oxygen to people with carbon monoxide poisoning?
- What factors influence the degree to which a salt will dissolve?

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. 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. The relationships between salt solubility, pH, and free energy will be encountered in subsequent units. Subsequent units will also 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 AT A GLANCE

Topic	Suggested Skill
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.
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).
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).
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.

Go to AP Classroom to assign the **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. 187 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.

SUGGESTED SKILL

Argumentation

6.D

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

TOPIC 7.1

Introduction to Equilibrium

Required Course Content

LEARNING OBJECTIVE

7.1.A

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

ESSENTIAL KNOWLEDGE

7.1.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.

7.1.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.

7.1.A.3

The equilibrium state is dynamic. The forward and reverse processes continue to occur at equal rates, resulting in no net observable change.

7.1.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.

TOPIC 7.2

Direction of Reversible Reactions

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.2.A Explain the relationship between the direction in which a reversible reaction proceeds and the relative rates of the forward and reverse reactions.	**7.2.A.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.

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 7.3

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

- The Exam > **2019 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE

7.3.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

7.3.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 partial 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

$$a\,\mathrm{A} + b\,\mathrm{B} \rightleftarrows c\,\mathrm{C} + d\,\mathrm{D}$$

the law of mass action indicates that 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: $K_p = \dfrac{(P_\mathrm{C})^c(P_\mathrm{D})^d}{(P_\mathrm{A})^a(P_\mathrm{B})^b}$

> ***Exclusion Statement:*** *Conversion between K_c and K_p will not be assessed on the AP Exam. 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

7.3.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

Exclusion Statement: *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.*

7.3.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.

SUGGESTED SKILL

Mathematical Routines

5.C

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

AVAILABLE RESOURCES

- The Exam > **2019 Chief Reader Report**

TOPIC 7.4

Calculating the Equilibrium Constant

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.4.A Calculate K_c or K_p based on experimental observations of concentrations or pressures at equilibrium.	**7.4.A.1** Equilibrium constants can be determined from experimental measurements of the concentrations or partial pressures of the reactants and products at equilibrium.

TOPIC 7.5

Magnitude of the Equilibrium Constant

SUGGESTED SKILL

Argumentation

6.D

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

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.5.A Explain the relationship between very large or very small values of K and the relative concentrations of chemical species at equilibrium.	**7.5.A.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.

SUGGESTED SKILL

Mathematical Routines

5.A

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

TOPIC 7.6

Properties of the Equilibrium Constant

Required Course Content

LEARNING OBJECTIVE

7.6.A

Represent a multistep process with an overall equilibrium expression, using the constituent K expressions for each individual reaction.

ESSENTIAL KNOWLEDGE

7.6.A.1

When a reaction is reversed, K is inverted.

7.6.A.2

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

7.6.A.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.

7.6.A.4

Since the expressions for K and Q have identical mathematical forms, all valid algebraic manipulations of K also apply to Q.

TOPIC 7.7
Calculating Equilibrium Concentrations

Required Course Content

LEARNING OBJECTIVE

7.7.A

Identify the concentrations or partial pressures of chemical species at equilibrium based on the initial conditions and the equilibrium constant.

ESSENTIAL KNOWLEDGE

7.7.A.1

The concentrations or partial pressures of species at equilibrium can be predicted given the balanced reaction, initial concentrations, and the appropriate K.

7.7.A.2

When $Q < K$, the reaction will proceed with a net consumption of reactants and generation of products. When $Q > K$, the reaction will proceed with a net consumption of products and generation of reactants. When $Q = K$, the system is at dynamic equilibrium; both forward and reverse reactions proceed at the same rate, and the proportion of reactants and products remains constant.

SUGGESTED SKILL

Representing Data and Phenomena

3.A

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

AVAILABLE RESOURCES

- The Exam > **2019 Chief Reader Report**

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).

TOPIC 7.8

Representations of Equilibrium

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.8.A Represent a system undergoing a reversible reaction with a particulate model.	**7.8.A.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.

TOPIC 7.9

Introduction to Le Châtelier's Principle

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**

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.9.A Identify the response of a system at equilibrium to an external stress, using Le Châtelier's principle.	**7.9.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. **7.9.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.

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**
- The Exam > **2022 Chief Reader Report**

TOPIC 7.10

Reaction Quotient and Le Châtelier's Principle

Required Course Content

LEARNING OBJECTIVE

7.10.A

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

ESSENTIAL KNOWLEDGE

7.10.A.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.

7.10.A.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.

TOPIC 7.11

Introduction to Solubility Equilibria

SUGGESTED SKILL

Mathematical Routines

5.B

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

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.11.A Calculate the solubility of a salt based on the value of K_{sp} for the salt.	**7.11.A.1** The dissolution of a salt is a reversible process whose extent can be described by K_{sp}, the solubility-product constant.
	7.11.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.
	7.11.A.3 The solubility rules (see 4.7.A.5) can be quantitatively related to K_{sp}, in which K_{sp} values >1 correspond to soluble salts.
	7.11.A.4 The molar solubility of one or more species in a saturated solution can be used to calculate the K_{sp} of a substance.

SUGGESTED SKILL

Question and Method

2.F

Explain how modifications to an experimental procedure will alter results.

TOPIC 7.12

Common-Ion Effect

Required Course Content

LEARNING OBJECTIVE

7.12.A

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

7.12.A.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.

AP CHEMISTRY

UNIT 8

Acids and Bases

11–15%
AP EXAM WEIGHTING

~14–16
CLASS PERIODS

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

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

Progress Check 8

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

- Long

UNIT
8

11–15% AP EXAM WEIGHTING

~14–16 CLASS PERIODS

Acids and Bases

ESSENTIAL QUESTIONS

- How is pH related to the concentration and strength of an acid, a base, or a mixture of them?
- How does acid or base strength relate to the concentrations of reactants and products when a system reaches equilibrium?
- Why are some acids stronger than others?
- 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. 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 or weak base-strong acid 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 encounter difficulty 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 face challenges with unit conversion, or they can confuse half-equivalence, equivalence, and endpoint. Students may also struggle to understand what is represented in different types of titration curves. 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. The half-equivalence point is a helpful reference point to visualize ratios of acid/conjugate base, particularly when combined with particulate representations.

UNIT AT A GLANCE

Topic	Suggested Skill
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.C** 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.
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.
8.11 pH and Solubility	**2.D** Make observation or collect data from representations of laboratory setups or results, while attending to precision where appropriate.

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

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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. 187 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

LEARNING OBJECTIVE

8.1.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

8.1.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 $H^+(aq)$ and $H_3O^+(aq)$ are often used interchangeably for the aqueous ion of hydrogen. Hydronium ion and $H_3O^+(aq)$ are preferred, but $H^+(aq)$ is also accepted on the AP Exam.

8.1.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

8.1.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

8.1.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.

Required Course Content

LEARNING OBJECTIVE

8.2.A

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

ESSENTIAL KNOWLEDGE

8.2.A.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 and the conjugate base of the acid. 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.

8.2.A.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 a group I hydroxide and double the initial concentration of a group II hydroxide, 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

LEARNING OBJECTIVE

8.3.A

Explain the relationship among pH, pOH, and concentrations of all species in a solution of a monoprotic weak acid or weak base.

ESSENTIAL KNOWLEDGE

8.3.A.1

Weak acids react with water to produce hydronium ions. However, only a small percentage of molecules of a weak acid will ionize in this way. 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.

8.3.A.2

A solution of a weak acid involves equilibrium between an un-ionized acid and its conjugate base. The equilibrium constant for this reaction is K_a, often reported as pK_a. The pH of a weak acid solution can be determined from the initial acid concentration and the pK_a.

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

EQN: $pK_a = -\log K_a$

8.3.A.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.

continued on next page

LEARNING OBJECTIVE

8.3.A

Explain the relationship among pH, pOH, and concentrations of all species in a solution of a monoprotic weak acid or weak base.

ESSENTIAL KNOWLEDGE

8.3.A.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: $pK_b = -\log K_b$

8.3.A.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). The percent ionization can also be calculated from the initial concentration of the acid (base) and the equilibrium concentration of any of the species in the equilibrium expression.

8.3.A.6

For any conjugate acid-base pair, the acid ionization constant and base ionization constant are related by K_w:

EQN: $K_w = K_a \times K_b$

EQN: $pK_w = pK_a + pK_b$

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

- The Exam > **2023 Chief Reader Report**

TOPIC 8.4

Acid-Base Reactions and Buffers

Required Course Content

LEARNING OBJECTIVE

8.4.A

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

ESSENTIAL KNOWLEDGE

8.4.A.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.

8.4.A.2

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

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

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 8.9.A.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:

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

continued on next page

LEARNING OBJECTIVE

8.4.A

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

ESSENTIAL KNOWLEDGE

8.4.A.3

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

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

If the weak base is in excess, then a buffer solution is formed, and the pH can be determined from the $\mathrm{H{-}H}$ 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:

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

8.4.A.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:

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

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?**
- The Exam > **2022 Chief Reader Report**

TOPIC 8.5

Acid-Base Titrations

Required Course Content

LEARNING OBJECTIVE

8.5.A

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

8.5.A.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.

8.5.A.2

At the equivalence point for titrations of monoprotic acids or bases, 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.

8.5.A.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.

continued on next page

LEARNING OBJECTIVE

8.5.A

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

8.5.A.4

At the equivalence point, pH is determined by the major species in solution. Strong acid and strong base titrations result in neutral pH at the equivalence point. However, in titrations of weak acids (weak bases), the conjugate base of the weak acid (conjugate acid of the weak base) is present at the equivalence point and can undergo proton-transfer reactions with the surrounding water, producing basic (acidic) solutions.

8.5.A.5

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 $\mathrm{p}K_a$ associated with each proton in a weak polyprotic acid.

> ***Exclusion Statement:*** *Computation of the concentration of each species present in the titration curve for polyprotic acids will not be assessed on the AP Exam. Such computations for titration of monoprotic acids are within the scope of the course (see 8.4.A.2 and 8.4.A.3), as is qualitative reasoning regarding what species are present in large versus small concentrations at any point in a titration of a polyprotic acid.*

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

LEARNING OBJECTIVE

8.6.A

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

ESSENTIAL KNOWLEDGE

8.6.A.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.

i. 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.

ii. Carboxylic acids are one common class of weak acid.

iii. Strong bases (such as group I and II hydroxides) have very weak conjugate acids.

iv. Common weak bases include nitrogenous bases such as ammonia as well as carboxylate ions.

v. 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

- The Exam > **2022 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE

8.7.A

Explain the relationship between the predominant form of a weak acid or base in solution at a given pH and the $\mathrm{p}K_a$ of the conjugate acid or the $\mathrm{p}K_b$ of the conjugate base.

ESSENTIAL KNOWLEDGE

8.7.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 $\mathrm{p}K_a$ of the acid in that solution. When solution $\mathrm{pH} <$ acid $\mathrm{p}K_a$, the acid form has a higher concentration than the base form. When solution $\mathrm{pH} >$ acid $\mathrm{p}K_a$, the base form has a higher concentration than the acid form.

8.7.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.

8.7.A.3

To ensure accurate results in a titration experiment, acid-base indicators should be selected that have a $\mathrm{p}K_a$ close to the pH at the equivalence point.

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
8.8.A 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.	**8.8.A.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

LEARNING OBJECTIVE

8.9.A

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

8.9.A.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: $\mathrm{pH} = \mathrm{p}K_a + \log\frac{[A^-]}{[HA]}$

Exclusion Statement: *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.*

Exclusion Statement: *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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
8.10.A 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.	**8.10.A.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. **8.10.A.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.

TOPIC 8.11

pH and Solubility

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

- The Exam > **2022 Chief Reader Report**

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
8.11.A Identify the qualitative effect of changes in pH on the solubility of a salt.	**8.11.A.1** The solubility of a salt is pH sensitive when one of the constituent ions is a weak acid, a weak base, or the hydroxide ion. These effects can be understood qualitatively using Le Châtelier's principle. ***Exclusion Statement:*** *Computations of solubility as a function of pH will not be assessed on the AP Exam.*

AP CHEMISTRY

UNIT 9

Thermodynamics and Electrochemistry

7–9%
AP EXAM WEIGHTING

~10–13
CLASS PERIODS

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

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

Progress Check 9

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

- Short
- Long

UNIT 9

7–9% AP EXAM WEIGHTING

~10–13 CLASS PERIODS

Thermodynamics and Electrochemistry

ESSENTIAL QUESTIONS

- Why do some chemical reactions occur without intervention, but others require the input of energy?
- How can we determine the conditions under which a chemical or physical transformation is likely to occur?
- How is electrical energy generated using chemical reactions?

Developing Understanding

This unit allows students to connect principles and calculations across Units 1–8. 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 higher energy that products may have in these 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 AT A GLANCE

Topic	Suggested Skill
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.
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 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.
9.7 Coupled Reactions	4.D Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.
9.8 Galvanic (Voltaic) and Electrolytic Cells	2.F Explain how modifications to an experimental procedure will alter results.
9.9 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).
9.10 Cell Potential Under Nonstandard Conditions	6.D Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.
9.11 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 **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. 187 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	9.8	**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	9.11	**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**
- The Exam > **2019 Chief Reader Report**

TOPIC 9.1

Introduction to Entropy

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
9.1.A Identify the sign and relative magnitude of the entropy change associated with chemical or physical processes.	**9.1.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. **9.1.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

LEARNING OBJECTIVE

9.2.A

Calculate the standard entropy change for a chemical or physical process based on the absolute entropies (standard molar entropies) of the species involved in the process.

ESSENTIAL KNOWLEDGE

9.2.A.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**
- The Exam > **2019 Chief Reader Report**

SUGGESTED SKILL

Argumentation

6.E

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

AVAILABLE RESOURCES

- The Exam > **2017 Chief Reader Report**
- The Exam > **2019 Chief Reader Report**

TOPIC 9.3

Gibbs Free Energy and Thermodynamic Favorability

Required Course Content

LEARNING OBJECTIVE

9.3.A

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

ESSENTIAL KNOWLEDGE

9.3.A.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°.

9.3.A.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.

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

continued on next page

LEARNING OBJECTIVE

9.3.A

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

ESSENTIAL KNOWLEDGE

9.3.A.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.

9.3.A.5

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

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

9.3.A.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.

TOPIC 9.4

Thermodynamic and Kinetic Control

Required Course Content

LEARNING OBJECTIVE

9.4.A

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

ESSENTIAL KNOWLEDGE

9.4.A.1

Many processes that are thermodynamically favored do not occur to any measurable extent, or they occur at extremely slow rates.

9.4.A.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.

Required Course Content

LEARNING OBJECTIVE

9.5.A

Explain whether a process is thermodynamically favored using the relationships between K, ΔG°, and T.

ESSENTIAL KNOWLEDGE

9.5.A.1

The phrase “thermodynamically favored” ($\Delta G^\circ < 0$) means that the products are favored at equilibrium ($K > 1$) under standard conditions.

9.5.A.2

The equilibrium constant is related to free energy by the equations

EQN: $K = e^{-\Delta G^\circ/RT}$

and

EQN: $\Delta G^\circ = -RT \ln K$.

9.5.A.3

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

9.5.A.4

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

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

Free Energy of Dissolution

Required Course Content

LEARNING OBJECTIVE

9.6.A

Explain the relationship between the solubility of a salt and changes in the enthalpy and entropy that occur in the dissolution process.

ESSENTIAL KNOWLEDGE

9.6.A.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.

TOPIC 9.7

Coupled Reactions

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

LEARNING OBJECTIVE

9.7.A

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

ESSENTIAL KNOWLEDGE

9.7.A.1

An external source of energy can be used to make a thermodynamically unfavorable process occur. Examples include:

i. Electrical energy to drive an electrolytic cell or charge a battery.

ii. Light to drive the overall conversion of carbon dioxide to glucose in photosynthesis.

9.7.A.2

A desired product can be formed by coupling a thermodynamically unfavorable reaction that produces that product to a favorable reaction (e.g., the conversion of ATP to ADP in biological systems). In the coupled system, the individual reactions share one or more common intermediates. The sum of the individual reactions produces an overall reaction that achieves the desired outcome and has $\Delta G^\circ < 0$.

SUGGESTED SKILL

Question and Method

2.F

Explain how modifications to an experimental procedure will alter results.

TOPIC 9.8

Galvanic (Voltaic) and Electrolytic Cells

Required Course Content

LEARNING OBJECTIVE

9.8.A

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

ESSENTIAL KNOWLEDGE

9.8.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.

9.8.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.

9.8.A.3

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

Exclusion Statement: *Labeling an electrode as positive or negative will not be assessed on the AP Exam.*

TOPIC 9.9

Cell Potential and Free Energy

Required Course Content

LEARNING OBJECTIVE

9.9.A

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

ESSENTIAL KNOWLEDGE

9.9.A.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).

9.9.A.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.

9.9.A.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: $\Delta G^\circ = -nFE^\circ$

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

- The Exam > **2018 Chief Reader Report**

SUGGESTED SKILL

Argumentation

6.D

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

AVAILABLE RESOURCES

- The Exam > **2022 Chief Reader Report**

TOPIC 9.10

Cell Potential Under Nonstandard Conditions

Required Course Content

LEARNING OBJECTIVE

9.10.A

Explain the relationship between deviations from standard cell conditions and changes in the cell potential.

ESSENTIAL KNOWLEDGE

9.10.A.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.

9.10.A.2

Equilibrium arguments such as Le Châtelier's principle do not apply to electrochemical systems, because the systems are not in equilibrium.

9.10.A.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	ESSENTIAL KNOWLEDGE
9.10.A Explain the relationship between deviations from standard cell conditions and changes in the cell potential.	**9.10.A.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.

SUGGESTED SKILL

Mathematical Routines

5.B

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

TOPIC 9.11

Electrolysis and Faraday's Law

Required Course Content

LEARNING OBJECTIVE

9.11.A

Calculate the amount of charge flow based on changes in the amounts of reactants and products in an electrochemical cell.

ESSENTIAL KNOWLEDGE

9.11.A.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:

i. Number of electrons transferred

ii. Mass of material deposited on or removed from an electrode (as in electroplating)

iii. Current

iv. Time elapsed

v. Charge of ionic species

EQN: $I = q/t$

AP CHEMISTRY

Laboratory Investigations

Lab Experiments

Student-directed, inquiry-based lab experience supports the AP Chemistry course and the AP Course Audit curricular requirements. It provides opportunities for students to design experiments, collect data, apply mathematical routines and methods, and refine testable explanations and predictions. Teachers are expected to devote a minimum of 25 percent of instructional time to lab investigations and to conduct at least 16 hands-on lab investigations to support the learning objectives in the course framework. Additionally, teachers are expected to provide guided inquiry-based labs for at least 6 of the 16 lab investigations.

Note: Virtual labs do not count towards the 25 percent of instructional time spent conducting hands-on labs.

Lab Manuals

The AP Program publishes **AP Chemistry Guided-Inquiry Experiments: Applying the Science Practices** to support the guided inquiry lab requirement for the course. This lab manual isn't required, but the teacher manual is free and available online. Publishers of chemistry textbooks also typically offer an associated lab manual. Science classroom supply companies may also offer them. Teachers should consider the course audit requirements, student needs, and cost before purchasing or requiring students to purchase.

Lab Notebooks and Student Workbooks

Many publishers and science classroom material distributors offer affordable lab notebooks and student workbooks with associated practice problems and solutions. Students can use any type of notebook to fulfill the lab notebook requirement, even an online document. Teachers should consider their own needs and those of their students when deciding what type of lab notebook to use. The ACS Style Guide, available from the American Chemical Society, is another important resource for the lab notebook (**acs.org**).

Lab Materials

AP Chemistry is a college-level course, but the equipment and chemicals needed for the labs are comparable to those required for a high school-level chemistry course. A list of commonly used instruments, lab bench equipment, and chemicals for AP Chemistry can be found in the appendix of the **AP Chemistry Guided-Inquiry Experiments: Applying the Science Practices** lab manual. A supportive school and district will help provide an adequate learning environment in which to conduct lab investigations. Most lab manuals provide a list of materials and equipment needed for each lab investigation. Before purchasing, teachers should consult their lab manual and calculate how much of a particular substance may be needed for the number of students they have.

It is important that the AP Chemistry lab program be adapted to local conditions and funding even while it aims to offer students a well-rounded experience with experimental chemistry. Adequate lab facilities should be provided so that each student has a work space where equipment and materials can be left overnight if necessary. Students will need access to basic lab equipment and glassware (e.g., beakers, Bunsen burners, and balances) in addition to some specialized equipment, such as spectrophotometers and pH meters, to complete the recommended labs. None of the recommended labs requires the use of probes or computer sensors for data collection, which are more expensive tools, though they can be used if available. It's recommended that teachers have a computer and projector to show computer-based animations and simulations for many of the prelab activities for lab investigations. However, a paper-based alternative can easily be provided if the equipment is unavailable. Students may use computers or graphing calculators to analyze data and present their findings, but they do not need to do so.

There are avenues that teachers can explore as a means of getting access to more expensive equipment, such as computers, spectrophotometers, high-quality analytical balances, and probes. Equipment like spectrophotometers can often be rented for short periods of time from instrument suppliers. Chemical companies often have equipment that classrooms can borrow; company representatives should have this information. Alternatively, local colleges or universities may allow high school students to complete a lab as a field trip on their campus, or they may allow teachers to borrow their equipment. They may even donate their old equipment. Some schools have partnerships with local businesses that can help with lab equipment and materials. There are many grant programs that teachers can apply to for funds to purchase equipment and supplies, including Hach grants from the American Chemical Society. Teachers can also utilize online donation sites such as Donors Choose and Adopt-A-Classroom.

Lab Time

To qualify for accreditation by the American Chemical Society, college chemistry departments typically schedule a weekly lab period of three hours. It is critical that lab work is an important part of an AP Chemistry course so that it is comparable to a college general chemistry course. Data shows that increased lab time is correlated with higher AP scores. Flexible or modular scheduling must be implemented in order to meet the time requirements.

Recommended Experiments

The AP Chemistry Exam directly assesses the learning objectives of the course framework, which means the inclusion of appropriate experiments aligned with those learning objectives is important for student success. Teachers should select experiments that provide students with the broadest lab experience possible.

The following is a list of recommended labs that includes the associated techniques that students will practice in that particular lab. Upon completion of the lab program, students should be able to describe how to collect data, reduce data to form conclusions, and identify and discuss relevant sources of error. Students should report recorded data and quantitative conclusions drawn from the data with appropriate precision (i.e., significant figures). Students should also develop an understanding of how changes in the design of the experiments would impact the validity and accuracy of their results. Many questions on the AP Exam are written in an experimental context, so these skills will prove invaluable for both concept comprehension and exam performance.

Use the absorption of light to determine the identity and/or concentration of an analyte in solution. This includes understanding how the quantities in Beer's law relate to the experimental setup, selecting a wavelength that will generate unambiguous data regarding the chemical species of interest, and using standard solutions to generate a calibration curve or measure the molar absorptivity.

Use differences in intermolecular forces to separate a mixture into its components or to determine the identity of components of a mixture. This includes using chromatography to separate and quantitatively identify the various components of a mixture.

Determine the formula of a compound by measuring the stoichiometry of the reaction of that compound with known reagents. This includes understanding how the product will be collected and massed (e.g., collection of evolved gas or filtering and washing of a solid) and how the data collected allows determination of the reaction stoichiometry.

Use gravimetric analysis to determine the amount of an analyte in a mixture. This includes selecting a reagent that will selectively precipitate the chemical species of interest and understanding how the solubility of the precipitate influences the experimental uncertainty and how to collect and mass the precipitate.

Use titration to determine the concentration of an analyte in a solution. This includes understanding how precise volumes of reactants can be effectively dispensed, knowing how to evaluate when the end point of the titration is reached from various means (e.g., change in color or conductivity), and understanding how to utilize reaction stoichiometry to determine analyte concentrations.

Determine the rate law of a chemical reaction. This includes selecting an appropriate measure of reaction rate or concentration (e.g., pressure, mass, color) and determining the rate law from either the time trace of concentration versus time or the dependence of initial rate on initial concentrations.

Use calorimetry to determine the change in enthalpy of a process. Experiments may be limited to constant pressure and include heating/cooling, phase transition, dissolution of a solid, and chemical reactions. Students should understand how to identify the subsystems involved in the heat exchange, how to use the measured temperature changes to determine the amount of heat exchanged, and how to determine the enthalpy of the process.

Build electrochemical cells to determine the characteristics of an electrochemical reaction. This includes preparation of a cell corresponding to the reaction of interest, measuring voltages and other quantities to characterize a voltaic cell, and utilizing external power sources to perform an electrolysis experiment.

Explore the impact of disturbances on an equilibrium system. This includes determining factors that impact the position of equilibrium and measuring how these disturbances impact the position of equilibrium.

Use titration to characterize an acid or base solution. In addition to the aspects discussed above regarding titrations, this includes using the data to determine concentration, pK_a or pK_b, of a monoprotic or polyprotic acid or base.

Prepare a buffer solution. This includes selecting appropriate buffer components and determining the concentrations needed to meet the target pH and buffer capacity, selecting the reagents needed to prepare the solution, and characterizing the resulting solutions to confirm that it meets the targets.

Note: Many of these labs can be broken down into two or more labs to meet the 16 labs requirement and to satisfy the 25 percent instructional time required. This is not an exhaustive list. Teachers should feel free to build in additional lab work that helps students develop strong procedural, safety, and instrumentation skills.

How to Set Up a Lab Program

Getting Students Started

It is possible to modify any traditional lab in order to make it a structured, guided, or open inquiry experiment. Designing and implementing inquiry-based labs that support student learning can be challenging. Teachers may want to consider collaborating with other teachers, attending workshops about inquiry-based labs (e.g., POGIL, SWH, or other chemistry education conferences or workshops) or consulting resources related to inquiry in the lab in order to become more skilled in implementing inquiry in their classrooms and labs.

For teachers who currently do verification lab activities, a first step toward including more inquiry in their curriculum is to do structured-inquiry lab activities. For example, teachers can have students work in groups investigating a variable (mass, concentration, temperature) over a range. Students can then observe what effect it has on a factor, data, make a graph, and ultimately infer an answer based on the graph of the pooled data.

To modify a cookbook lab, teachers can think the question: *What characteristics make this lab "cookbook" rather than inquiry?* Other good questions include: *At what inquiry level is the lab currently? Toward what inquiry level should this lab move?* Even small changes to the lab can provide students with more of an inquiry experience. Three examples of how teachers can modify common cookbook experiments follow. Note that these are not detailed prescriptions for complete experiments but suggestions for how to think about inquiry modifications. For more detailed guided inquiry labs, see **AP Chemistry Guided-Inquiry Experiments: Applying the Science Practices**.

1. **Molar volume of a gas.** A traditional version of this lab asks students to determine the molar volume of a gas by combining hydrochloric acid with magnesium. Students are given a set amount of magnesium and a set procedure. A possible guided inquiry question could be: *How does the mass of magnesium ribbon used affect the molar volume of a gas?* In a guided inquiry version, all students use a different amount of magnesium to do the reaction; they can do several trials with different amounts. Students then put their end results and calculated data on the board and analyze the data.
2. **Qualitative analysis of ions in solution.** In a typical version of this lab, students are given a series of known solutions and a set procedure for identifying various ions. After observing the reactions of the known solutions, students repeat the same procedure with an unknown solution. In a possible inquiry-based version of this lab, give students a set of test reagents and a series of known solutions and ask them to design procedures to distinguish between three or four ions. Different student groups will work with different known ions. Next, students share their data and the procedures they designed in a class discussion. They then use their combined data and work together to design a procedure to identify the ions in an unknown solution containing several ions.
3. **Electrochemistry—galvanic cells.** Traditionally, students are given a set procedure to construct a number of galvanic cells from various metals and solutions and measure the cell potential of each one. An inquiry-based way to conduct this lab entails student groups investigating different factors that affect cell potential, such as electrode identity or concentration of reactant solutions. Each group studies only one factor and then groups come together to share data and discuss patterns. Students would then be challenged to apply their learning to create the battery with the greatest cell potential.

Observations and Data Manipulation

Students must practice making careful observations and accurately recording what they observe. Too frequently students confuse what they see with what they think they are supposed to see. They should be encouraged to be accurate reporters, even when their findings seem to conflict with what they are led to expect by the textbook or lab procedure. Proper interpretation of observations is also important. Students should be able to find evidence of chemical change (color change, precipitate formation, temperature change, gas evolution, etc.) and its absence (in the identification of spectator ions, for example). Students should know how to make and interpret quantitative measurements correctly. This includes knowing which piece of apparatus is appropriate for making the measurement.

Communication and Group Collaboration

Lab work is an excellent means through which students can develop and practice communication skills. Success in subsequent work in the field of chemistry depends heavily on an ability to communicate chemical observations, ideas, and conclusions. Working in a truly collaborative manner to plan and execute experiments will help students learn oral communication skills and practice teamwork. Students should be encouraged to take individual responsibility for the success or failure of the collaboration.

Lab Safety

A successful AP Chemistry lab program will instill in each student a lifelong "safety sense" that will ensure their safe transition into more advanced work in college or university labs or into the industrial workplace environment. It is important that certain concerns regarding lab safety be addressed in every chemistry course.

- All facilities should conform to federal, state, and local laws and guidelines pertaining to the safety of students and teachers.
- Teachers with a limited background in chemistry should receive additional safety training specific to chemistry labs before teaching AP Chemistry.
- Lab experiments and demonstrations should not be carried out if they could expose students to unnecessary risks or hazards.
- Students should be fully informed of potential lab hazards relating to chemicals and apparatuses before performing specific experiments.
- Storage and disposal of hazardous chemicals must be done in accordance with local regulations and policies. Teachers and students should know what these regulations are.

Basic lab safety instruction should be an integral part of each lab experience. Topics that should be covered include:

- Simple first aid for cuts and thermal and chemical burns
- Use of safety goggles, eye washes, body showers, fire blankets, and fire extinguishers
- Safe handling of glassware, hot plates, burners and other heating devices, and electrical equipment
- Proper interpretation of Material Safety Data Sheets (MSDS) and hazard warning labels
- Proper use and reuse practices (including proper labeling of interim containers) for reagent bottles

Material and Equipment Use

Students must learn the skills necessary to use the following ordinary equipment: beakers, flasks, test tubes, crucibles, evaporating dishes, watch glasses, burners, plastic and glass tubing, stoppers, valves, spot plates, funnels, reagent bottles, wash bottles, droppers, and measuring equipment.

The list of measuring equipment includes: balances (single pan, double pan, triple beam), thermometers (ºC), barometers, graduated cylinders, burets, volumetric pipets, graduated pipets, volumetric flasks, ammeters, voltmeters, pH meters, and spectrophotometers. A more comprehensive list of laboratory equipment can be found in Appendix C of **AP Chemistry Guided-Inquiry Experiments: Applying the Science Practices**.

Processes and Procedures

Students should be familiar with the following general types of chemical lab work:

- Synthesis of compounds (solid and gas)
- Separations (precipitation and filtration, dehydration, centrifugation, distillation, chromatography)
- Titration using indicators and meters
- Spectrophotometry/colorimetry
- Gravimetric analysis

Microscale Experiments

One important change in chemistry lab instruction in recent years has been the introduction of microscale experiments. Teachers can determine whether microscale experiments are appropriate for their students and classroom/lab space. Here are some benefits to consider:

- Decreased cost of chemicals acquisition and disposal
- Reduced storage space requirements and safer storage
- Less need for elaborate lab facilities in schools
- Greater care needed by students to obtain and observe results
- Shorter experiment times as well as easier and faster cleanup
- Ability to carry out some experiments that were once restricted to demonstration because of their hazards in macroscale

AP CHEMISTRY

Instructional Approaches

Selecting and Using Course Materials

In addition to using a college-level textbook that will cover the required course content, students are required to perform lab investigations for 25 percent of instructional time (with a mix of both teacher-directed and guided inquiry investigations). Students are also required to keep a lab notebook to document all of their lab work. Further, it is common practice for students to work several practice problems that may or may not be provided in their textbook. See the Laboratory Investigation section starting on page 179 for more details on lab materials.

Teachers who are beginning or adapting lab programs can also find helpful resources online at AP Central and the AP Chemistry Teacher Community. The resource section of the AP Chemistry Teacher Community offers reviews of textbooks, articles, websites, and other teaching resources. Teachers can also request advice or opinions regarding all issues relating to AP Chemistry, including the labs.

Textbooks

The AP Chemistry course requires the use of a college-level textbook. It is unlikely that a high school-level textbook will cover the content and skills of the course in the depth necessary to succeed on the AP Exam. It is important to select a textbook that covers the content of the AP Chemistry course as detailed in the course framework. Additionally, a textbook that focuses on skill instruction will help provide students opportunities to practice constructing particulate representations of matter, solving single- and multi-step problems, and explaining chemical phenomena.

AP Central provides an example textbook list to help determine whether a text is considered appropriate in meeting the AP Chemistry Course Audit resource requirement. Teachers can also select textbooks locally.

Guided Inquiry in AP Chemistry

Inquiry-based instruction is encouraged in both the chemistry classroom and the lab. However, the guided inquiry model of instruction differs substantially from the traditional model of lab and/or classroom learning. Instead of seeking confirmation of concepts, inquiry-based labs and classroom activities allow students, with guidance, to observe phenomena, explore ideas, and find patterns. This allows students to answer questions they have developed themselves.

Here are some essential features of guided inquiry instruction in both the classroom and the lab.

- Learner selects among questions and poses new questions.
- Learner is directed to collect certain data.
- Learner is given data and asked to analyze it.
- Learner is given the data and told how to analyze it.
- Learner is guided in the process of formulating explanations from evidence.
- Learner is directed toward areas and sources of scientific knowledge.
- Learner is coached in the development of communication.

Instructional Strategies

The AP Chemistry course framework outlines the concepts and skills students need to master to be successful on the AP Exam. In order to address those concepts and skills effectively, it helps to incorporate a variety of instructional approaches into daily lessons and activities. The following table presents strategies that can help students apply their understanding of course concepts.

Strategy	Definition	Purpose	Example
Critique Reasoning	Through collaborative discussion, students respond to the arguments of others and question the use of a mathematical routine, assumptions, and/or conjectures to improve understanding, justify, and communicate conclusions.	Helps students learn from each other as they make connections between mathematical routines and learn to verbalize their understanding and support their arguments with reasoning and data that makes sense to peers.	Give students the series of steps (equations) for a chemical reaction, the rate law for such, and a list of suggested mechanisms and have student groups think about which mechanism is consistent with the rate law and series of steps. Have them discuss their predictions about what the proposed mechanism for the reaction should be. Then have groups share their proposal and reasoning for other groups to evaluate and provide feedback.
Demos with Q&A	Students make a prediction based on prior knowledge or misconceptions. Then the teacher introduces or reinforces a chemical concept via a demonstration, by which students address their understanding or misconceptions through observations or clarifying questions.	Engages students by quickly gaining their attention and stimulating their curiosity about what is happening with the phenomena being demonstrated and addresses their misconceptions or builds upon their prior knowledge.	Students think boiling liquids will be hot. First put a sample of liquid butane in a sealed container. Then have students cause boiling to occur by touching the outside of the container; the container develops frost on the outside as boiling occurs. Have students address their initial misconceptions through group discussion.

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Strategy	Definition	Purpose	Example
Explore Representations	Students create, interpret, and/or analyze pictures, tables, graphs, lists, equations, models, and/or verbal expressions to interpret text or data. Students observe information or create visual representations to find a trend.	Helps students organize information using multiple ways to present data and answer a question or show a problem's solution. Builds comprehension and facilitates discussion by representing information in visual form. Helps to identify patterns that may be used to make predictions.	Students are told the boiling point of CCl_4 is higher than CH_2Cl_2. Have them create one representation of the interactions of at least two CCl_4 molecules and a second representation of the interactions of at least two CH_2Cl_2 molecules at the boiling point. Have students use their particulate representations to explain why one boiling point is higher than the other.
Identify a Subtask	Students break a problem into smaller pieces whose outcomes lead to a solution.	Helps students organize the pieces of a complex problem and reach a complete solution.	After providing students with a particular chemical reaction (and associated concentrations of all species), ask them to determine the concentration of all species once the reaction is in equilibrium. Teachers can employ an ICE (initial concentration, change in concentration, and equilibrium concentration) chart to help students work through the subtasks of this complicated problem.
Manipulatives	Students use objects to examine relationships between the objects and information given.	Provides a visual representation of data that supports comprehension of information in a problem.	Have students use molecule building kits to construct Lewis structures. Then have them use these structures and VSEPR theory to predict the molecular geometry and overall polarity of molecules.
Post-Lab Discussion	Students discuss the understanding of a concept to lead to a consensus on its meaning. Students discuss the extension of the laboratory protocol to other chemical systems.	Helps clarify misconceptions and deepen understanding of content. Allows students to troubleshoot errors and focus on solutions that may arise when they do the same procedures themselves.	After performing a titration to determine the concentration of an unknown, have students present their answers and compare with the "known" answer. Then have them evaluate each other's answers and calculations to determine what (if any) errors led to a discrepancy between the experimental value and the known value.

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Strategy	Definition	Purpose	Example
Predict & Confirm	Students make conjectures about what results will develop in an activity and confirm or modify the conjectures based on outcomes.	Stimulates thinking by making, checking, and correcting predictions based on evidence from the outcome.	Given a particular molecular structure and using their understanding of kinetic molecular theory and intermolecular forces, have students make predictions about chemical species (e.g., boiling point, macroscopic observations when pressure changes, interactions with other chemical species).
Process Oriented Guided Inquiry Learning (POGIL)	Students work in small (self-managed) teams to collaboratively engage in small activities (including data sets and a series of guiding questions) that follow the learning cycle of exploration to build understanding of a concept and then apply that knowledge or process in a new context.	Helps students develop mastery of content through the construction of their own understanding and through the development of reasoning skills as they discuss their thought processes with others.	After students review a data set regarding periodic trends, give them a series of guided questions to rationalize the data in the context of atomic structure. Then have them apply the model they developed with extended questions or additional data.
Simulations	Students interact with chemically realistic simulations and can either enter or alter parameters by which the simulation will reveal the consequences or changes therein.	Helps students visualize, interact with, and manipulate variables associated with difficult chemistry concepts and phenomena as well as particulate representations of matter.	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 generated. Have them check their answers upon completion of the simulation.
Think-Pair-Share	Considering and thinking about a topic or question and then writing what has been learned; pairing with a peer or a small group to share ideas; sharing ideas and discussion with a larger group.	Helps students to construct meaning about a topic or question; to test thinking in relation to the ideas of others; to prepare for a discussion with a larger group.	Given a problem pertaining to thermodynamic favorability, have students think through how enthalpy and/or entropy drives the thermodynamic favorability of the reaction. Then have students pair up and explain their reasoning for whether or not the reaction is thermodynamically favorable and what is driving that favorability. After they have discussed their responses, have them share with other pairs to get feedback on their rationale.

Developing the Science Practices

Throughout the course, students will develop science practices that are fundamental to the discipline of chemistry. Students will benefit from multiple opportunities to develop these practices in a scaffolded manner.

The tables that follow provide sample activities and instructional strategies for incorporating the individual skills into the course.

Science Practice 1: Describe models and representations, including across scales

The ability to use models and "pictures" to explain/represent what is happening at the particulate level is fundamental to understanding chemistry. Before being able to explain or represent what is happening at the particulate level, students must be able to identify the components of and describe what is happening in a model, representation, or graph of a chemical system or phenomenon.

Science Practice 1: *Models and Representations*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
1.A *Describe the components of and quantitative information from models and representations that illustrate particulate-level properties only.*	Identify the bond angle from a Lewis dot structure. From an electron configuration, identify the number of valence electrons.	Give students a 3-D molecular structure then ask them to describe several bond angles and bond lengths within the molecule.	Manipulatives
1.B *Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.*	Given a Lewis dot structure, identify the intermolecular force that is congruent with a macroscopic observation.	Give students structures on a sheet of paper and ask them to describe the evaporation rate of each molecule in comparison with each other. Swipe the substances on a lab table to help students observe which evaporates faster and then ask them to describe why.	Demos with Q&A

Science Practice 2: Determine scientific questions and methods

Using guided inquiry instruction, students can construct and/or discover knowledge with an understanding of how scientists study the natural world. Inquiry teaching expands beyond lab investigations and field experiments to include classroom experiences, such as scientific model development and revision and peer-to-peer critique of explanations. Student activities that support the learning of science concepts through scientific inquiry in AP classrooms may include:

- Reading about known scientific theories and ideas
- Generating scientifically oriented questions
- Making predictions or posing preliminary hypotheses
- Planning investigations
- Making observations
- Using tools to gather and analyze data
- Constructing explanations
- Creating, critiquing, and revising models
- Engaging in scientific argumentation
- Reviewing known theories and concepts in light of empirical data
- Communicating the results of an experiment

Science Practice 2: *Question and Method*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
2.A *Identify a testable scientific question based on an observation, data, or a model.*	After reviewing a student's method of investigation and associated macroscopic observations, identify the question the student is seeking to answer.	Have students observe substances generating different-colored flames. Then have them develop a question that could generate data to explain this phenomenon.	Demos with Q&A
2.B *Formulate a hypothesis or predict the results of an experiment.*	Predict the formula of ionic compounds based on the position of the elements in the periodic table.	Give students ionization energy data from various elements and have them rationalize the relationship of the charge of the ion to its position on the periodic table and its electronic structure.	POGIL
2.C *Identify experimental procedures that are aligned to a scientific question (which may include a sketch of a lab setup).*	What experimental procedure would separate a precipitate after mixing two solutions?	Given that a precipitate is a solid trapped in a solution, have students identify the procedure of filtration to separate the precipitate from the solution.	Explore Representations
2.D *Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.*	Collect absorbances of a solution at varying concentrations to create a calibration curve of the solution.	Using a series of concentration of solutions, have students observe the color and relate that color to the absorbance.	Predict and Confirm

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Science Practice 2: *Question and Method (cont'd)*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
2.E *Identify or describe potential sources of experimental error.*	Predict a slower rate due to a lower concentration.	Have students implement a gravimetric analysis lab to determine the amount of iron in a sample. Have them discuss the effect a wet sample would have on the calculated percentage of iron.	Post-Lab Discussion
2.F *Explain how modifications to an experimental procedure will alter results.*	Students have been given a table of data and results and asked to explain why one result is different than the other based on change in procedure.	Give students data where a catalyst has been added to a chemical system and ask them to explain what would happen to the rate of reaction.	Post-Lab Discussion

Science Practice 3: Create representations or models of chemical phenomena

After being able to identify components in a model or representation and describe what is happening, students should be able to construct such representations, models, or graphs to represent chemical systems, phenomena, and interactions at the particulate level.

Science Practice 3: *Representing Data and Phenomena*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
3.A *Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.*	Student creates a titration curve based on pH as a function of volume of titrant added.	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).	Post-Lab Discussion
3.B *Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).*	Students are given the density of two different substances and asked to create a representation of the spacing between particles of each of the substances.	Have students use pieces of circular paper to represent molecules then move them closer together to represent higher density substances.	Manipulative

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Science Practice 3: *Representing Data and Phenomena (cont'd)*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
3.C *Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).*	Students are provided with two substances that mix together and are asked to rationalize the macroscopic observations by drawing a particulate representation of the interacting molecules.	Students are told that hexane does not mix with water but ethanol does. Have them create a particulate representation of each of the mixtures (illustrating the interactions between the molecules that allow/disallow the solubility).	Explore Representations

Science Practice 4: Analyze and interpret models and representations on a single scale or across multiple scales

After learning the skill of constructing models, representations, or graphs for chemical systems or phenomena, students should be able to analyze and interpret such models for the purpose of explaining what is happening at the particulate level. Students should also be able to evaluate the accuracy or correctness of the model or representation in illustrating or demonstrating what is happening within a chemical system or phenomenon.

Science Practice 4: *Model Analysis*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
4.A *Predict and/or explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.*	Explain why the ionization energy of fluorine is greater than that of oxygen.	Give students a table of ionization energies of various elements and have them explain the trends of values in terms of atomic structure.	POGIL
4.B *Explain whether a model is consistent with chemical theories.*	Students are asked to draw a Lewis dot diagram that is consistent with experimental data.	Give students a sample of a gas and tell them that the pressure of the gas is lower than expected. Have them explain the deviation from predicted ideal gas behavior.	Think-Pair-Share
4.C *Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.*	Students are told that an ionic substance dissolved in water is able to conduct electricity. Students must identify the particulate representation that explains the experimental observation.	Give students a buffer solution represented as a reversible reaction and ask them to explain how the pH will change after adding water.	Critique Reasoning

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Science Practice 4: *Model Analysis (cont'd)*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
4.D *Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.*	Students are given a particulate representation of a weak acid and asked to explain whether the representation matches the observed pH.	Give students data about an experimental rate law and ask them to determine (through guided questions) which mechanism is consistent with that rate law.	POGIL

Science Practice 5: Solve problems using mathematical relationships

Mathematical reasoning skills are essential for success in chemistry. Students should be able to cite reasons for using a particular mathematical routine. Students should also be able to use mathematics to solve problems that describe the physical world.

Science Practice 5: *Mathematical Routines*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
5.A *Identify quantities needed to solve a problem from given information (e.g., text, mathematical expressions, graphs, or tables).*	What data needs to be collected to determine the empirical formula of an ionic compound?	Ask students to determine the molar heat of an ionic solid dissolved in water. Have them identify what measurements must be taken to complete the task. Then have students work with one another to discuss responses and report their findings.	Think-Pair-Share
5.B *Identify an appropriate theory, definition, or mathematical relationship to solve a problem.*	A student has been given the reaction of a weak acid dissociating in water. The student identifies which of the equilibrium expressions is used to calculate the K_a of the chemical phenomena.	Given a gaseous equilibrium process, ask students to identify the expression that can be ultimately be used to calculate the K_p.	Identify a Subtask
5.C *Explain the relationship between variables within an equation when one variable changes.*	A gas with a given pressure and volume has a new volume applied. The student is asked to describe what the new pressure would be.	Place a balloon into a vacuum pump. Ask students to predict what will happen as the air is removed. Remove the air and ask students to explain the relationship between pressure and volume.	Demo with Q&A

continued on next page

Science Practice 5: *Mathematical Routines (cont'd)*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
5.D *Identify information presented graphically to solve a problem.*	A student is given a titration curve and asked to determine the volume that can be used to calculate the concentration of the titrant.	Give students a calibration curve of varying concentrations of a $CoCl_2$ solution. Knowing the absorbance of an unknown concentration of a solution of $CoCl_2$, have them interpolate the solution's concentration.	Explore Representations
5.E *Determine a balanced chemical equation for a given chemical phenomena.*	Transform a molecular equation into a net ionic equation for a particular chemical phenomenon.	Give students a description of the reaction between silver nitrate and sodium chloride then ask them to write the net ionic equation for this precipitation reaction.	Explore Representations
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).*	Calculate the amount of product made when you mix a particular amount of X and a particular amount of Y.	Provide students with the masses of two reactants (and the associated chemical equation for the subsequent reaction). Have them use dimensional analysis and stoichiometry to calculate the maximum yield of the product.	Identify a Subtask

Science Practice 6: Develop an explanation or scientific argument

The ability to formulate a coherent argument, that is, to make a claim that is clearly articulated and supported by experimental evidence, is at the core of the scientific method. These arguments arise from the iterative processes of experimentation, observation, and interpretation. Claims (conclusions) made by scientists are ultimately shared with the broader community for peer review and further validation. Consequently, students need to practice:

- Articulating a claim
- Providing qualitative and/or quantitative evidence to support their claim
- Justifying the inclusion or exclusion of particular pieces of evidence in supporting their claim
- Connecting qualitative and/or quantitative evidence to chemical theories and models to justify their line of reasoning

Science Practice 6: *Argumentation*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
6.A *Make a scientific claim.*	The temperature of the equilibrium mixture is increased to 425 K. Will the value of K_p increase, decrease, or remain the same? Justify your prediction.	Show students a demo on the change in volume of a gas based on change in pressure, have students ask questions and come up with a mathematical relationship between pressure and volume of a gas. Then ask them to make a claim (prediction) about what will happen to the volume of a gas based on a particular change in pressure. Have students critique each other's claims based on the mathematical relationship determined during the Q&A.	▪ Demo with Q&A ▪ Critique Reasoning
6.B *Support a claim with evidence from experimental data.*	A chemist successfully separates a mixture of $CCl_4(g)$ and HCl(g) by cooling the mixture to 70°C. At this temperature, the CCl_4 condenses and HCl remains in the gaseous state. Using this experimental data, what can be inferred about the intermolecular forces in $CCl_4(l)$ and HCl(l)?	After investigating three different dyes using chromatography, have students determine which of the three dyes is the most polar based on macroscopic observations and 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.	▪ Post-Lab Discussion ▪ Explore Representations ▪ Critique Reasoning
6.C *Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.*	Students have been given a list of different substances and their corresponding boiling points. Students must make a claim about the connection between the substances' boiling points and their intermolecular forces.	Students are told the boiling point of CCl_4 is higher than CH_2Cl_2. Have them create one representation of the interactions of at least two CCl_4 molecules and a second representation of the interactions of at least two CH_2Cl_2 at the boiling point. Have them use their particulate representations to explain why one boiling point is higher than the other.	Explore Representations

continued on next page

Science Practice 6: *Argumentation (cont'd)*

Skill	Questions/Tasks	Sample Activities	Instructional Strategies
6.D *Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.*	Students must determine how the percent ionization of a weak acid is altered by the addition of water.	Give students the percent ionization of HF at a particular concentration and volume. Ask them whether the percent ionization is altered once the volume of the solution is doubled after the addition of water. Have students justify their response qualitatively or quantitatively.	Critique Reasoning
6.E *Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.*	Students must explain in terms of KMT why the rate of a reaction increases as a function of concentration and/or temperature.	Have students observe a simulation of a chemical reaction and measure the rate of formation of product as a function of concentration and/or temperature.	Simulations
6.F *Explain the connection between experimental results and chemical concepts, processes, or theories.*	Given a particular system at equilibrium, use Le Châtelier's principle to explain the direction of shift on the system (toward reactants or toward products) as a result of a particular stress.	Have students will view an online simulation of a chemical system in equilibrium and ask them to explain what direction the reaction will shift prior to simulating a series of stresses.	▪ Simulation ▪ Predict & Confirm
6.G *Explain how potential sources of experimental error may affect the experimental results.*	In a particular trial for a titration experiment to determine the concentration of an acid, a student added more NaOH (*aq*) than was needed to reach the end point. Would this error increase, decrease, or have no effect on the calculated acid concentration?	After performing a gravimetric analysis experiment to determine the mass percent of I^- in a tablet containing KI and an inert, water soluble substance, have students compare calculated values of the mass percent of I^- in the tablet and identify sources of experimental error that may account for their varied results.	▪ Post-Lab Discussion ▪ Think-Pair-Share

AP CHEMISTRY

Exam Information

Exam Overview

*The AP Chemistry Exam assesses student application of the science practices and understanding of the learning objectives outlined in the course framework. The exam is 3 hours and 15 minutes long and includes 60 multiple-choice questions and 7 free-response questions. A scientific or graphing calculator is recommended for use on **both sections** of the exam. Students are provided with the periodic table and a formula sheet that lists specific and relevant formulas for use on the exam (see Appendixes). The details of the exam, including exam weighting and timing, can be found below:*

Section	Question Type	Number of Questions	Exam Weighting	Timing
I	**Multiple-choice questions**	**60**	**50%**	**90 minutes**
II	**Free-response questions**		**50%**	**105 minutes**
	Long questions (10 points each)	3		
	Short questions (4 points each)	4		

The AP Exam assesses the nine units of the course with the following exam weighting on the multiple-choice section:

Units of Instruction	Exam Weighting
Unit 1: Atomic Structure and Properties	**7–9%**
Unit 2: Compound Structure and Properties	**7–9%**
Unit 3: Properties of Substances and Mixtures	**18–22%**
Unit 4: Chemical Reactions	**7–9%**
Unit 5: Kinetics	**7–9%**
Unit 6: Thermochemistry	**7–9%**
Unit 7: Principles of Equilibrium	**7–9%**
Unit 8: Acids and Bases	**11–15%**
Unit 9: Thermodynamics and Electrochemistry	**7–9%**

How Student Learning Is Assessed on the AP Exam

Section I: Multiple-Choice

Science Practices 1, 2, 4, 5, and 6 are all assessed in the multiple-choice section with the following exam weighting (Science Practice 3 is not assessed in the multiple-choice section):

Science Practice	Exam Weighting
Practice 1: Models and Representations	**8–12%**
Practice 2: Question and Method	**8–12%**
Practice 4: Model Analysis	**23–30%**
Practice 5: Mathematical Routines	**35–42%**
Practice 6: Argumentation	**8–12%**

Section II: Free-Response

All six science practices are assessed in the free-response section with the following exam weighting:

Science Practice	Exam Weighting
Practice 1: Models and Representations	**2–4%**
Practice 2: Question and Method	**10–16%**
Practice 3: Representing Data and Phenomena	**8–16%**
Practice 4: Model Analysis	**5–9%**
Practice 5: Mathematical Routines	**43–53%**
Practice 6: Argumentation	**15–24%**

Task Verbs Used in Free-Response Questions

The following task verbs are commonly used in the free-response questions:

Calculate: Perform mathematical steps to arrive at a final answer, including algebraic expressions, properly substituted numbers, and correct labeling of units and significant figures.

Describe: Provide the relevant characteristics of a specified topic.

Determine: Make a decision or arrive at a conclusion after reasoning, observation, or applying mathematical routines (calculations).

Estimate: Roughly calculate numerical quantities, values (greater than, equal to, less than), or signs (negative, positive) of quantities based on experimental evidence or provided data.

Explain: Provide information about how or why a relationship, process, pattern, position, situation, or outcome occurs, using evidence and/or reasoning to support or qualify a claim. Explain "how" typically requires analyzing the relationship, process, pattern, position, situation, or outcome; whereas, explain "why" typically requires analysis of motivations or reasons for the relationship, process, pattern, position, situation, or outcome. Also phrased as "give one reason."

Identify/Indicate/Circle: Indicate or provide information about a specified topic in words or by circling given information. Also phrased as "What is?" or "Which?" or other interrogatory words.

Justify: Provide evidence to support, qualify, or defend a claim and/or provide reasoning to explain how that evidence supports or qualifies the claim.

Make a claim: Make an assertion that is based on evidence or knowledge.

Predict/Make a prediction: Predict the causes or effects of a change in, or disruption to, one or more components in a relationship, pattern, process, or system.

Represent/Draw/Write an Equation/Complete a Diagram: Use appropriate graphs, symbols, words, and/or models to describe phenomena, characteristics, and/or relationships.

Sample Exam Questions

The sample exam questions that follow illustrate the relationship between the course framework and AP Chemistry Exam and serve as examples of the types of questions that appear on the exam. After the sample questions is a table that shows which skill, learning objective(s), and unit each question relates to. The table also provides the answers to the multiple-choice questions.

Section I: Multiple-Choice

The following are examples of the kinds of multiple-choice questions found on the exam.

$$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6$$

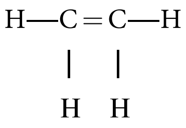
1. Which of the following species has the electron configuration shown above?

   (A) O

   (B) Ne

   (C) K^+

   (D) $C1^+$



$$\begin{array}{ccccccc} H & — & C & = & C & — & H \\ & & | & & | & & \\ & & H & & H & & \end{array}$$

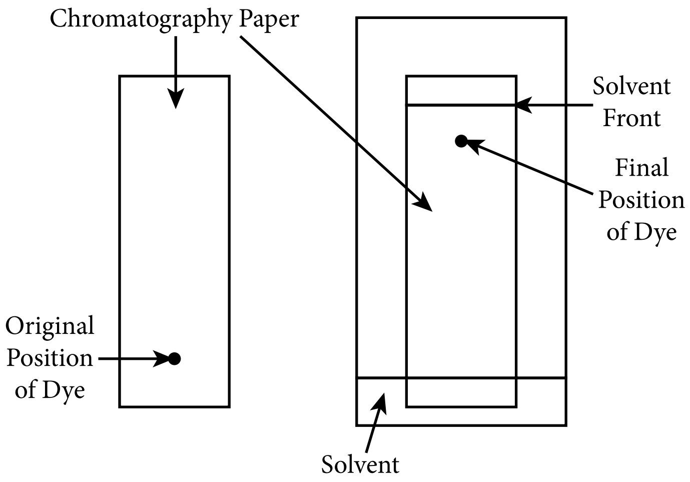
2. A Lewis diagram for the molecule C_2H_4 is shown above. In the actual C_2H_4 molecule, the H-C-H bond angles are closest to

   (A) 90°

   (B) 109.5°

   (C) 120°

   (D) 180°



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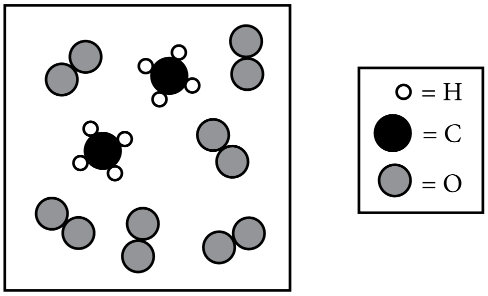
3. Based on the results of the paper chromatography experiment shown above, which of the following can be concluded about the dye?

   (A) It has a small molar mass.

   (B) It has weak intermolecular forces.

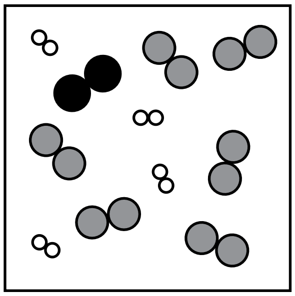
   (C) It has a weaker attraction for the stationary phase than it has for the mobile phase.

   (D) It has a stronger attraction for the stationary phase than it has for the mobile phase.

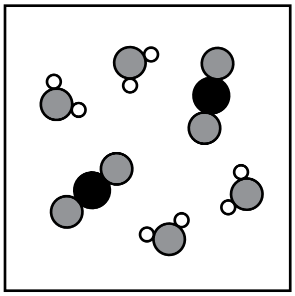


4. The reactants represented above are placed in a vessel and a reaction occurs. Which of the following best represents the contents of the vessel after the reaction has proceeded as completely as possible?

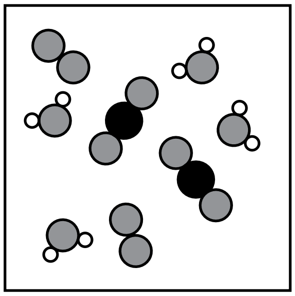
(A)



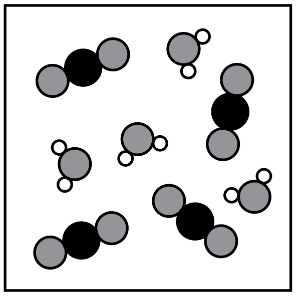
(B)



(C)



(D)

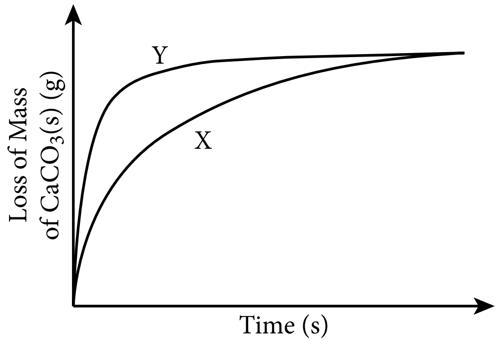


Initial buret reading	2.17 mL
Final buret reading	22.17 mL

5. An antacid tablet containing $Mg(OH)_2(s)$ (molar mass 58.3 g/mol) is titrated with a 0.100 *M* solution of $HNO_3(aq)$. The end point is determined by using an indicator. Based on the data in the table above, what was the mass of the $Mg(OH)_2(s)$ in the antacid tablet?
   (A) 0.0583 g
   (B) 0.583 g
   (C) 5.83 g
   (D) 58.3 g

$$HCl(aq) + CaCO_3(s) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

The reaction between $HCl(aq)$ and $CaCO_3(s)$ is represented by the equation above. Two separate trials were carried out using $CaCO_3(s)$ samples of the same mass, but one sample was a single piece of $CaCO_3(s)$, and one sample was composed of small pieces of $CaCO_3(s)$. The loss of mass of $CaCO_3(s)$ as a function of time for both trials is shown in the graph below.



6. Which of the curves, X or Y, represents the reaction with small pieces of $CaCO_3(s)$, and why?
   (A) Curve X, because it shows that the reaction proceeded at a uniform rate.
   (B) Curve X, because it takes a shorter time for the reaction to go to completion due to the larger surface area of $CaCO_3(s)$.
   (C) Curve Y, because it shows that the reaction proceeded at a nonuniform rate.
   (D) Curve Y, because it takes a shorter time for the reaction to go to completion due to the larger surface area of $CaCO_3(s)$.

Cup	**Material of Spoon**	**Initial Temperature of Spoon (°C)**	**Mass of Spoon (g)**	**Specific Heat Capacity (J/g °C)**
A	Aluminum	20	10.0	0.90
B	Ceramic	20	10.0	0.80
C	Steel	20	20.0	0.45
D	Silver	20	40.0	0.23

7. Four identical 50 mL cups of coffee, originally at 95°C, were stirred with four different spoons, as listed in the table above. In which cup will the temperature of the coffee be highest at thermal equilibrium? (Assume that the heat lost to the surroundings is negligible.)
   (A) Cup A
   (B) Cup B
   (C) Cup C
   (D) Cup D

$$Ag^+ + (aq) + 2\,NH_3(aq) \rightleftarrows [Ag\,(NH_3)_2]^+\,(aq)\ K = 1 \times 10^7$$

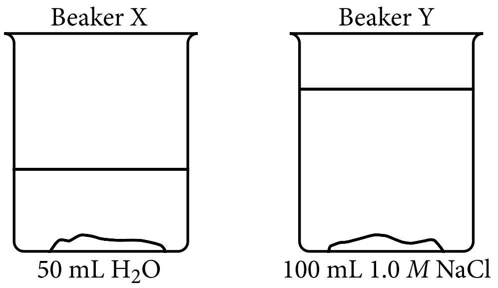
8. Equal volumes of 0.1 M $AgNO_3(aq)$ and 0.4 M $NH_3(aq)$ are mixed and allowed to reach the equilibrium represented above. Which of the following correctly lists the equilibrium concentrations of the $Ag^+(aq)$, $NH_3(aq)$, and $[Ag(NH_3)_2]^+(aq)$ in order from least to greatest?
   (A) $[Ag^+]_{eq} < [NH_3]_{eq} < [[Ag(NH_3)_2]^+]_{eq}$
   (B) $[NH_3]_{eq} < [Ag^+]_{eq} < [[Ag(NH_3)_2]^+]_{eq}$
   (C) $[Ag(NH_3)_2]^+]_{eq} < [Ag^+]_{eq} < [NH_3]_{eq}$
   (D) $[Ag^+]_{eq} < [[Ag(NH_3)_2]^+]_{eq} < [NH_3]_{eq}$

$$N_2(g) + 3\,H_2(g) \rightleftarrows 2\,NH_3(g)$$

A 2.0 L reaction vessel contains an equilibrium mixture of the system represented above. The partial pressures of the components of the mixture at equilibrium are listed in the table below.

P_{N_2}	P_{H_2}	P_{NH_3}
0.30 atm	0.50 atm	0.20 atm

9. Which of the following is the best estimate of the total pressure of the system when the volume of the container is reduced to 1.0 L at a constant temperature?
   (A) $P_{total} = 1.00$ atm
   (B) $1.00 \text{ atm} < P_{total} < 2.00$ atm
   (C) $P_{total} = 2.00$ atm
   (D) $P_{total} > 2.00$ atm



10. Beaker X contains 50 mL of distilled water and beaker Y contains 100 mL of 1.0 *M* NaCl. Solid AgCl is added to each of the beakers. After thoroughly stirring the contents of the beakers, some solid AgCl remains at the bottom of each beaker, as shown above. Which of the following is true?

    (A) $[Ag^+]$ is zero in both beakers.

    (B) $[Ag^+]$ is the same, but not zero, in both beakers.

    (C) $[Ag^+]$ is greater in beaker X.

    (D) $[Ag^+]$ is greater in beaker Y.

11. The value of K_w for water at 0°C is 1×10^{-15}. What is the pOH of water at 0°C?

    (A) 6.5

    (B) 7.0

    (C) 7.5

    (D) 8.0

Half-Reaction	$E°$(V)
$Ag^+(aq) + e^- \rightarrow Ag(s)$	0.80
$Cr^{3+}(aq) + 3\ e^- \rightarrow Cr(s)$	−0.41

12. Based on the standard reduction potentials in the table above, what is the value of $E°$ for a standard galvanic cell made with Ag/Ag^+ and Cr/Cr^{3+} half-cells?

    (A) 0.39 V

    (B) 1.21 V

    (C) 1.99 V

    (D) 2.81 V

Questions 13–15 refer to the information below.

A 0.50 g sample of $Mg(s)$ was placed in a solution of $HCl(aq)$, where it reacted completely.

13. Which of the following equations best represents the reacting species in the reaction described above?

    (A) $Mg(s) + 2\ H^+(aq) \rightarrow Mg^{2+}(aq) + H_2(g)$

    (B) $Mg(s) + HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$

    (C) $Mg(s) + 2\ HCl(aq) \rightarrow MgCl_2(s) + 2\ H^+(aq)$

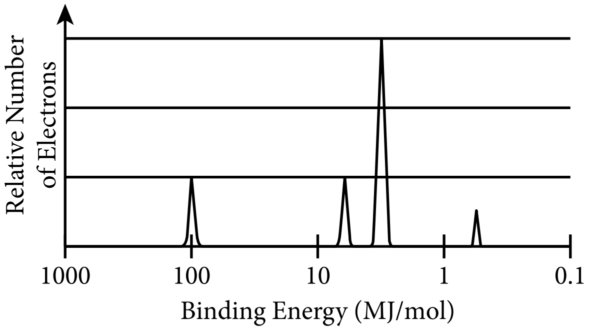
    (D) $Mg(s) + 2\ HCl(aq) \rightarrow Mg^{2+}(aq) + Cl_2(g) + H_2(g)$

14. In another experiment, a small piece of Mg(*s*) is weighed, then placed in a flask containing excess 1 *M* HCl(*aq*). The student wants to determine number of moles of gas produced. Which of the following is the best way to conduct the experiment for accurate data collection?
   (A) Conducting the experiment at different temperatures to see which generates the most gas
   (B) Completing the entire reaction in a large Erlenmeyer flask of known volume to measure the volume of the gas collected
   (C) Collecting the gas in a eudiometer tube and measuring the volume of the gas collected
   (D) Conducting the reaction in a graduated cylinder and measuring the volume of the gas collected

15. In a third experiment, 0.10 g samples of Mg(*s*) are placed in excess HCl(*aq*) of various concentrations: 0.050 *M*, 0.10 *M*, 0.25 *M*, and 0.50 *M*. The reactions are run in successive order from 0.050 *M* to 0.50 *M*, and the time required for each reaction to go to completion is recorded. As the concentration of HCl(*aq*) increases from 0.050 *M* to 0.50 *M*, which of the following is the expected result?
   (A) The reaction time increases, and the rate of the reaction decreases.
   (B) The reaction time decreases, and the rate of the reaction increases.
   (C) Both the reaction time and the rate of the reaction increase.
   (D) Both the reaction time and the rate of the reaction decrease.

Section II: Free-Response

The following are examples of the kinds of free-response questions found on the exam. Note that on the actual AP Exam, there will be three long free-response questions and four short free-response questions.



1. The complete photoelectron spectrum of an unknown element is given above.
   (a) Draw an X above the peak that corresponds to the orbital with electrons that are, on average, closest to the nucleus. Justify your answer in terms of Coulomb's law.
   (b) Based on the spectrum, write the complete electron configuration of the element.
   (c) On the graph, draw the peak(s) corresponding to the valence electrons of the element that has one more proton in its nucleus than the unknown element has.

2. The following questions relate to sulfur and some of its compounds.

(a) Write the balanced equation for the combustion of $S_8(s)$ to form $SO_2(g)$.

(b) Calculate the volume of $O_2(g)$, measured at 1.00 atm and 298 K, that is required to completely combust a 500.0 g sample of pure $S_8(s)$.

(c) A student claims that the combustion of S_8 is an oxidation-reduction reaction. Justify the claim by identifying the oxidation numbers of sulfur and oxygen both before and after the reaction.

(d) In the box below, draw a Lewis electron-dot diagram for one valid resonance structure of SO_2.

(e) Based on the diagram you drew in part (d), what is the approximate oxygen-sulfur-oxygen bond angle in SO_2?

SO_2 can be oxidized to form SO_3 according to the following equation.

$$2\ SO_2(g) + O_2(g) \rightarrow 2\ SO_3(g) \qquad \Delta H° = -198\ \text{kJ/mol}_{rxn}$$

(f) Is the value of $\Delta S°$ for the reaction represented above positive or negative? Justify your answer.

$$2\ SO_2(g) + O_2(g) \rightarrow 2\ SO_3(l)$$

(g) Is the magnitude of $\Delta H°$ for the reaction to form $SO_3(l)$, represented above, greater than, less than, or equal to the magnitude of $\Delta H°$ for the reaction to form $SO_3(g)$? Justify your answer.

(h) Based on the information above, how does the thermodynamic favorability of the reaction change as the temperature of the reaction system is decreased? Justify your answer.

Answer Key and Question Alignment to Course Framework

Multiple-Choice Question	Answer	Skill	Learning Objective	Essential Knowledge
1	C	1.A	1.5.A	1.5.A.3
2	C	6.C	2.7.A	2.7.A.2
3	C	2.D	3.9.A	3.9.A.1
4	C	5.C	4.5.A	4.5.A.1
5	A	5.F	4.6.A	4.6.A.1
6	D	6.F	5.1.A	5.1.A.3
7	B	5.F	6.4.A	6.4.A.1
8	D	5.F	7.7.A	7.7.A.1
9	B	5.F	7.9.A	7.9.A.1
10	C	5.F	7.12.A	7.12.A.1
11	C	5.F	8.1.A	8.1.A.4
12	B	5.F	9.9.A	9.9.A.2
13	A	5.E	4.2.A	4.2.A.3
14	C	2.C	3.4.A	3.4.A.1
15	B	2.B	5.2.A	5.2.A.1

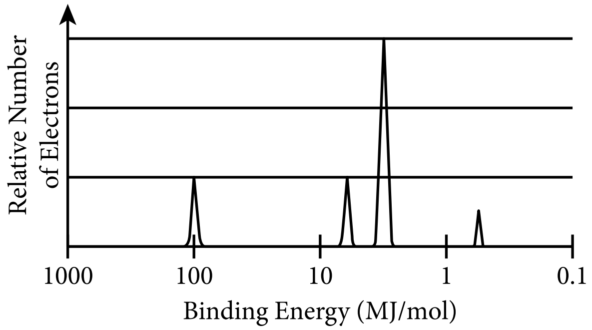
Free-Response Question	Question Type	Skill	Learning Objective
1	Short	3.A, 3.B, 6.D	1.6.A
2	Long	1.A, 3.B, 4.C, 5.C, 5.E, 5.F, 6.D	2.5.A, 2.7.A, 4.2.A, 4.5.A, 4.7.A, 6.9.B, 9.1.A, 9.3.A

The scoring information for the questions within this course and exam description, along with further exam resources, can be found on the **AP Chemistry Exam Page** on AP Central.

AP CHEMISTRY

Scoring Guidelines

Question 1: Short-Answer



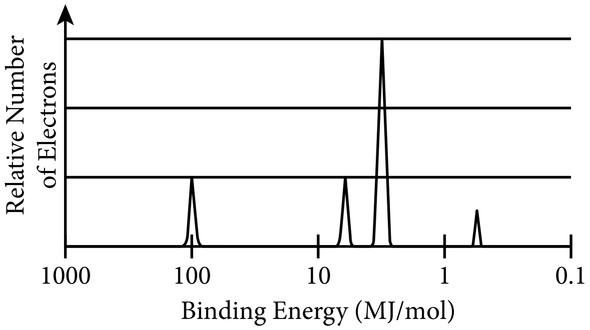
1. The complete photoelectron spectrum of an unknown element is given above.
   - (a) Draw an X above the peak that corresponds to the orbital with electrons that are, on average, closest to the nucleus. Justify your answer in terms of Coulomb's law.
   - (b) Based on the spectrum, write the complete electron configuration of the element.
   - (c) On the graph, draw the peak(s) corresponding to the valence electrons of the element that has one more proton in its nucleus than the unknown element has.

Scoring Guidelines for Question 1: Short-Answer — 4 points

Learning Objectives: 1.6.A

(a) Draw an X above the peak that corresponds to the orbital with electrons that are, on average, closest to the nucleus. Justify your answer in terms of Coulomb's law.

1 point 6.D 1.6.A



See the student's drawing.

One point for the X located above the leftmost peak (at 100 MJ/mol) in the spectrum with the justification that the electrons closest to the nucleus have the greatest binding energy because the strength of attraction between the charges (electron and nucleus) is greatest when the distance between them (*r*) is the least.

(b) Based on the spectrum, write the complete electron configuration of the element.

1 point 3.B 1.6.A

One point for the correct configuration.

$1s^2\ 2s^2\ 2p^6\ 3s^1$

(c) On the graph, draw the peak(s) corresponding to the valence electrons of the element that has one more proton in its nucleus than the unknown element has.

1 point 3.A 1.6.A

See the student's drawing.

One point if the peak is located just to the left of the rightmost peak in the spectrum.

One point if the height of the peak is twice the height of the rightmost peak in the spectrum.

1 point 3.A 1.6.A

Total for part (c) **2 points**

Total for question 1 **4 points**

Question 2: Long-Answer

2. The following questions relate to sulfur and some of its compounds.

   (a) Write the balanced equation for the combustion of $S_8(s)$ to form $SO_2(g)$.

   (b) Calculate the volume of $O_2(g)$, measured at 1.00 atm and 298 K, that is required to completely combust a 500.0 g sample of pure $S_8(s)$.

   (c) A student claims that the combustion of S_8 is an oxidation-reduction reaction. Justify the claim by identifying the oxidation numbers of sulfur and oxygen both before and after the reaction.

   (d) In the box below, draw a Lewis electron-dot diagram for one valid resonance structure of SO_2.

   (e) Based on the diagram you drew in part (d), what is the approximate oxygen-sulfur-oxygen bond angle in SO_2?

   SO_2 can be oxidized to form SO_3 according to the following equation.

$$2\ SO_2(g) + O_2(g) \rightarrow 2\ SO_3(g) \qquad \Delta H° = -198\ \text{kJ/mol}_{rxn}$$

   (f) Is the value of $\Delta S°$ for the reaction represented above positive or negative? Justify your answer.

$$2\ SO_2(g) + O_2(g) \rightarrow 2\ SO_3(l)$$

   (g) Is the magnitude of $\Delta H°$ for the reaction to form $SO_3(l)$, represented above, greater than, less than, or equal to the magnitude of $\Delta H°$ for the reaction to form $SO_3(g)$? Justify your answer.

   (h) Based on the information above, how does the thermodynamic favorability of the reaction change as the temperature of the reaction system is decreased? Justify your answer.

Scoring Guidelines for Question 2: Long-Answer — 10 points

Learning Objectives: 2.5.A 2.7.A 4.2.A 4.5.A 4.7.A 6.9.B 9.1.A 9.3.A

(a) Write the balanced equation for the combustion of $S_8(s)$ to form $SO_2(g)$. **1 point** 5.E 4.2.A

One point for the balanced equation.

$S_8(s) + 8\ O_2(g) \rightarrow 8\ SO_2(g)$

(b) Calculate the volume of $O_2(g)$, measured at 1.00 atm and 298 K, that is required to completely combust a 500.0 g sample of pure $S_8(s)$. **1 point** 5.F 4.5.A

One point for calculating the moles of O_2.

$$500.0\ g\ S_8 \times \frac{1\ \text{mol}\ S_8}{256.5\ g\ S_8} \times \frac{8\ \text{mol}\ O_2}{1\ \text{mol}\ S_8} = 15.60\ \text{mol}\ O_2$$

One point for calculating the volume of O_2. **1 point** 5.F 4.5.A

$$V = \frac{nRT}{P} = \frac{(15.60\ \text{mol})(0.08206\ \text{L}\cdot\text{atm}\cdot\text{mol}^{-1}\cdot\text{K}^{-1})(298\ \text{K})}{1.00\ \text{atm}} = 381\ \text{L}$$

Total for part (b) **2 points**

(c) A student claims that the combustion of $S_8(s)$ is an oxidation-reduction reaction. Justify the claim by identifying the oxidation numbers of sulfur and oxygen both before and after the reaction. **1 point** 1.A 4.7.A

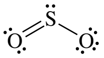
One point for all four correct oxidation numbers.

Oxidation numbers before the reaction: S = 0, O = 0

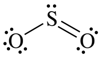
Oxidation numbers after the reaction: S = +4, O = –2

(d) In the box below, draw a complete Lewis electron-dot diagram for one valid resonance structure of $SO_2(g)$. **1 point** 3.B 2.5.A

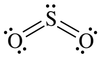
Any one of the three following diagrams is acceptable.



or



or



One point for the correct number of electrons.

One point for a valid Lewis diagram. **1 point** 3.B 2.5.A

Total for part (d) **2 points**

(e) Based on the diagram you drew in part (d), what is the approximate oxygen-sulfur-oxygen bond angle in SO_2? **1 point** 1.A 2.7.A

One point for an angle that is consistent with the student's Lewis structure: 120°

(f) SO_2 can be oxidized to form SO_3 according to the following equation. **1 point** 4.C 9.1.A

$2\ SO_2(g) + O_2(g) \rightarrow 2\ SO_3(g) \quad \Delta H^\circ = -198\ \text{kJ/mol}_{rxn}$

Is the value of ΔS° for the reaction represented above positive or negative? Justify your answer.

One point for indicating negative with a valid explanation that mentions the smaller number of moles of gas in the products.

- *Negative, because the reactants are three moles of gas but the products are only two moles of gas.*

(g) 2 $SO_2(g) + O_2(g) \rightarrow 2\ SO_3(l)$ **1 point** **6.D** **6.9.B**

Is the magnitude of $\Delta H°$ for the reaction to form SO_3 (*l*), represented above, greater than, less than, or equal to the magnitude of $\Delta H°$ for the reaction to form SO_3 (*g*)? Justify your answer.

One point for indicating greater magnitude with a valid justification:.

- *Greater, because the enthalpy of SO_3 (l) is lower than the enthalpy of SO_3 (g) (by an amount equal to the enthalpy of vaporization of SO_3 (l)), which makes the difference between the enthalpy of the reactants and the enthalpy of the products a larger amount.*

(h) Based on the information above, how does the thermodynamic favorability of the reaction change as the temperature of the reaction system is decreased? Justify your answer. **1 point** **5.C** **9.3.A**

One point for indicating an increased thermodynamic favorability along with a valid justification.

- *$\Delta G_{rxn} = \Delta H_{rxn} - T\Delta S_{rxn}$. Assuming that both ΔH_{rxn} and ΔS_{rxn} are constant, as the value of T is decreased, the smaller in value the term ($T\Delta S_{rxn}$) becomes, making the term (ΔH_{rxn}–$T\Delta S_{rxn}$) more negative. Thus ΔG_{rxn} becomes more negative, increasing the thermodynamic favorability of the reaction.*

Total for question 2 **10 points**

AP CHEMISTRY

Appendixes

AP CHEMISTRY

Appendix 1: Periodic Table of the Elements

PERIODIC TABLE OF THE ELEMENTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** 1.008																	2 **He** 4.00
3 **Li** 6.94	4 **Be** 9.01											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.30											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.87	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.38	31 **Ga** 69.72	32 **Ge** 72.63	33 **As** 74.92	34 **Se** 78.97	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.95	43 **Tc**	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57-71 *	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po**	85 **At**	86 **Rn**
87 **Fr**	88 **Ra**	89-103 †	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cn**	113 **Nh**	114 **Fl**	115 **Mc**	116 **Lv**	117 **Ts**	118 **Og**

*Lanthanoids	57 **La** 138.91	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm**	62 **Sm** 150.36	63 **Eu** 151.97	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.05	71 **Lu** 174.97
†Actinoids	89 **Ac**	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

AP CHEMISTRY

Appendix 2: Equations and Constants

AP® CHEMISTRY EQUATIONS AND CONSTANTS, EFFECTIVE 2025

UNIT SYMBOLS	
gram,	g
mole,	mol
liter,	L
meter,	m
second,	s
hertz,	Hz
atmosphere,	atm
millimeter of mercury,	mm Hg
degree Celsius,	°C
Kelvin,	K
joule,	J
volt,	V
coulomb,	C
ampere,	A

UNIT CONVERSIONS
1 hertz = 1 s^{-1}
1 atm = 760 mm Hg = 760 torr
K = °C + 273.15
$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$
$1 \text{ ampere} = \frac{1 \text{ coulomb}}{1 \text{ second}}$

METRIC PREFIXES		
Factor	Prefix	Symbol
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

ATOMIC STRUCTURE

$$E = h\nu$$

$$c = \lambda\nu$$

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

E = energy

ν = frequency

λ = wavelength

F = force

q = charge

r = separation

Planck's constant, $h = 6.626 \times 10^{-34}$ J s

Speed of light, $c = 2.998 \times 10^{8}$ m s^{-1}

Avogadro's number $= 6.022 \times 10^{23}$ mol^{-1}

GASES, LIQUIDS, AND SOLUTIONS

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$PV = nRT$$

$$P_A = P_{\text{total}} \times X_{\text{A}}, \text{ where } X_{\text{A}} = \frac{\text{moles A}}{\text{total moles}}$$

$$P_{\text{total}} = P_{\text{A}} + P_{\text{B}} + P_{\text{C}} + \ldots$$

$$n = \frac{m}{\boldsymbol{M}}$$

$$D = \frac{m}{V}$$

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

$$M = \frac{n_{solute}}{\text{L}_{solution}}$$

$$A = \varepsilon bc$$

P = pressure

V = volume

T = temperature

n = number of moles

X = mole fraction

m = mass

$\boldsymbol{M}$ = molar mass

D = density

KE = kinetic energy

v = velocity

M = molarity

A = absorbance

ε = molar absorptivity

b = path length

c = concentration

Gas constant, R = 8.314 J mol^{-1} K^{-1}

= 0.08206 L atm K^{-1} mol^{-1}

STP = 273.15 K and 1.0 atm

Ideal gas at STP = 22.4 L mol^{-1}

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KINETICS

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

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

$$\frac{1}{[\mathrm{A}]_t} - \frac{1}{[\mathrm{A}]_0} = kt$$

$$t_{1/2} = \frac{0.693}{k}$$

k = rate constant
t = time
$t_{1/2}$ = half-life

EQUILIBRIUM

$$K_c = \frac{[\mathrm{C}]^c[\mathrm{D}]^d}{[\mathrm{A}]^a[\mathrm{B}]^b}, \text{ where } a\,\mathrm{A} + b\,\mathrm{B} \rightleftarrows c\,\mathrm{C} + d\,\mathrm{D}$$

$$K_p = \frac{(P_\mathrm{C})^c(P_\mathrm{D})^d}{(P_\mathrm{A})^a(P_\mathrm{B})^b}$$

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

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

$$\mathrm{pH} = -\log[\mathrm{H_3O^+}], \qquad \mathrm{pOH} = -\log[\mathrm{OH^-}]$$

$$K_a = \frac{[\mathrm{H_3O^+}][\mathrm{A^-}]}{[\mathrm{HA}]}, \qquad K_b = \frac{[\mathrm{OH^-}][\mathrm{HB^+}]}{[\mathrm{B}]}$$

$$\mathrm{p}K_a = -\log K_a, \qquad \mathrm{p}K_b = -\log K_b$$

$$K_w = K_a \times K_b, \qquad \mathrm{p}K_w = \mathrm{p}K_a + \mathrm{p}K_b$$

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

Equilibrium Constants

K_c	(molar concentrations)
K_p	(gas pressures)
K_w	(water)
K_a	(acid)
K_b	(base)

THERMODYNAMICS/ELECTROCHEMISTRY

$$q = mc\Delta T$$

$$\Delta H^\circ_{reaction} = \sum \Delta H^\circ_{f\ products} - \sum \Delta H^\circ_{f\ reactants}$$

$$\Delta S^\circ_{reaction} = \sum S^\circ_{products} - \sum S^\circ_{reactants}$$

$$\Delta G^\circ_{reaction} = \sum \Delta G^\circ_{f\ products} - \sum \Delta G^\circ_{f\ reactants}$$

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

$$= -RT\ln K$$

$$= -nFE^\circ$$

$$I = \frac{q}{t}$$

$$E_{cell} = E^\circ_{cell} - \frac{RT}{nF}\ln Q$$

q = heat
m = mass
c = specific heat capacity
T = temperature
S° = standard entropy
H° = standard enthalpy
G° = standard Gibbs free energy
R = gas constant
K = equilibrium constant
n = number of moles of electrons
E° = standard potential
I = current (amperes)
q = charge (coulombs)
t = time (seconds)
Q = reaction quotient
Faraday's constant, F = 96,485 coulombs / 1 mol e^-

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