AP® Chemistry

Course Planning and Pacing Guide 1

Scott Balicki
Boston Latin School
Boston, Massachusetts

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Welcome to the AP® Chemistry Course Planning and Pacing Guides

This guide is one of four course planning and pacing guides designed for AP® Chemistry teachers. Each provides an example of how to design instruction for the AP course based on the author's teaching context (e.g., demographics, schedule, school type, setting).

These course planning and pacing guides highlight how the components of the *AP Chemistry Curriculum Framework* — the learning objectives, big ideas, conceptual understandings, and science practices — are addressed in the course. Each guide also provides valuable suggestions for teaching the course, including the selection of resources, instructional activities, laboratory investigations, and assessments. The authors have offered insight into the *why* and *how* behind their instructional choices — displayed in boxes along the right side of the individual unit plans — to aid in course planning for AP Chemistry teachers. Additionally, each author explicitly explains how he or she manages course breadth and increases depth for each unit of instruction.

The primary purpose of these comprehensive guides is to model approaches for planning and pacing curriculum throughout the school year. However, they can also help with syllabus development when used in conjunction with the resources created to support the AP Course Audit: the Syllabus Development Guide and the four Annotated Sample Syllabi. These resources include samples of evidence and illustrate a variety of strategies for meeting curricular requirements.

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Course Planning and Pacing by Unit

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Instructional Setting

Boston Latin School
Boston, Massachusetts

School	Boston Latin School is a public exam school serving students in grades 7–12; students gain entrance based on a combination of their grades in the fifth and sixth grades and their score on the competitive ISSE exam. Founded in 1635, Boston Latin School is the oldest public school in the United States. The school's mission statement is "Boston Latin School seeks to ground its students in a contemporary classical education as preparation for successful college studies, responsible and engaged citizenship, and a rewarding life."
Student population	Total enrollment of 2384 students: • 12.1 percent African American • 8.8 percent Hispanic • 48.8 percent Caucasian • 28.1 percent Asian • 2.2 percent multiracial/other
	• 98.8 percent regular education • 1.1 percent special education • 0.5 percent English language learners • 28.5 percent receive free or reduced-price lunch • Average daily student attendance: 96 percent • 99 percent of the members of the class of 2011 were accepted to four-year colleges

Instructional time	The academic year begins after Labor Day and goes until the end of June. Seniors are dismissed to graduate in mid-May, and juniors attend school through the end of the school year. Seniors have roughly 160 instructional days; juniors have roughly 180. • There are approximately 36 weeks of instructional time prior to the AP® Chemistry Exam • Five 44-minute class periods result in 220 instructional hours per week • After-school help sessions are available weekly • One full practice exam under authentic exam conditions is administered on a Saturday in March
Student preparation	AP Chemistry is offered as an elective to juniors and seniors who completed Chemistry 1 in their sophomore or junior year and earned at least a C average. Students who enroll in the course receive a two-part summer assignment, which is due at the end of July and the end of August. Students submit their solutions online via a Google Docs form. The assignment covers the equivalent of the first four chapters of the students' textbook, including such topics as atomic structure, measurement, dimensional analysis, and stoichiometry.
Textbooks and lab manuals	Brady, James E., and Fred Senese. *Chemistry: Matter and Its Changes*. 4th ed. Hoboken, NJ: Wiley, 2004. Hostage, David, and Martin Fossett. *Laboratory Investigations: AP* Chemistry*. Saddle Brook, NJ: Peoples Education, 2006.

Overview of the Course

AP Chemistry at Boston Latin School is intended to expose students to sophisticated chemical principles and concepts and fundamental laboratory technique. The central objective of the course is for students to connect the macroscale (the scale at which they observe phenomena) to the nanoscale (the scale at which atoms and molecules interact). Students demonstrate that they have made these connections symbolically, graphically, and mathematically throughout the year. Students are expected to synthesize and apply their knowledge, rather than memorize a mountain of facts, to be successful in my class.

Core concepts called *enduring understandings* and their applications via the *science practices* are the basis of the AP Chemistry curriculum. These concepts are organized around chemical principles called *big ideas* that permeate the entire course and focus on the following topics:

- Atoms, reactions, and stoichiometry
- Reactions involving electron transfer
- Chemical energy and thermodynamics
- Atomic and molecular structure
- Gases and intermolecular forces
- Kinetics
- General and solubility equilibrium
- Acid-base equilibrium

In my AP Chemistry class, I am the facilitator of student learning rather than the source of knowledge. My pedagogical goal is to design learning experiences outside of class through which students develop basic understanding of chemistry topics, subsequently using class time to guide students to confront their misconceptions, synthesize their knowledge, and develop more nuanced understandings. Prereading of class texts and Cornell note-taking precede instruction for all units. This enables class meetings to be student centered and follow a guided-inquiry model. Laboratory experiences allow students to simultaneously investigate new chemistry content, apply their knowledge, and become proficient in basic chemical technique. I expect students to progress in their ability to write laboratory reports over the year. Laboratory reports are, along with unit exams, summative assessments of student understanding. Such assessments allow me to prepare students for college success by providing them with frequent, detailed feedback on their evolving understanding of laboratory technique, and to evaluate their comprehension of AP Chemistry's big ideas, enduring understandings, and essential knowledge. Some chemistry labs are traditional, in which students follow a prescribed procedure to understand chemistry phenomena. Others are guided inquiry, in which students are given guidance for their technique, but have the ability to decide what data to collect and analyze. And some are pure inquiry, in which students are given minimal guidance regarding procedure, materials, data collection, or data analysis. Laboratory experiences account for at least 25 percent of class time.

Differentiating instruction is a constant challenge in AP Chemistry, considering the depth of knowledge that students need to attain in the course. Both inside and outside of class, students are exposed to a variety of instructional approaches, including Cornell notes, laboratory investigations, whiteboarding (sharing of work on individual whiteboards), inquiry with simulations, and jigsaw activities. Quizzes are given frequently, and are not averaged toward students' final grades. This makes the quizzes truly formative, and these, along with other frequent formative assessments, allow me to make instructional decisions based upon student performance.

AP Chemistry is a challenging class. Students at Boston Latin School who take the course often report that it is their most challenging class in high school. By making class student centered, making frequent use of formative assessments, differentiating instruction, and supporting students throughout their learning experiences, it is my hope that it is also their most rewarding class.

Big Ideas and Science Practices

AP Chemistry Big Ideas

Big Idea 1: The chemical elements are fundamental building materials of matter, and all matter can be understood in terms of arrangements of atoms. These atoms retain their identity in chemical reactions.

Big Idea 2: Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules and the forces between them.

Big Idea 3: Changes in matter involve the rearrangement and/or reorganization of atoms and/or the transfer of electrons.

Big Idea 4: Rates of chemical reactions are determined by details of the molecular collisions.

Big Idea 5: The laws of thermodynamics describe the essential role of energy and explain and predict the direction of changes in matter.

Big Idea 6: Any bond or intermolecular attraction that can be formed can be broken. These two processes are in a dynamic competition, sensitive to initial conditions and external perturbations.

Science Practices for AP Chemistry

A practice is a way to coordinate knowledge and skills in order to accomplish a goal or task. The science practices enable students to establish lines of evidence and use them to develop and refine testable explanations and predictions of natural phenomena. These science practices capture important aspects of the work that scientists engage in, at the level of competence expected of AP Chemistry students.

Science Practice 1: The student can use representations and models to communicate scientific phenomena and solve scientific problems.

1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.
1.2 The student can *describe representations and models* of natural or man-made phenomena and systems in the domain.
1.3 The student can *refine representations and models* of natural or man-made phenomena and systems in the domain.
1.4 The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.
1.5 The student can *re-express key elements* of natural phenomena across multiple representations in the domain.

Science Practice 2: The student can use mathematics appropriately.

2.1 The student can *justify the selection of a mathematical routine* to solve problems.
2.2 The student can *apply mathematical routines* to quantities that describe natural phenomena.
2.3 The student can *estimate numerically* quantities that describe natural phenomena.

Science Practice 3: The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course.

3.1 The student can *pose scientific questions*.
3.2 The student can *refine scientific questions*.
3.3 The student can *evaluate scientific questions*.

Science Practice 4: The student can plan and implement data collection strategies in relation to a particular scientific question.

4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question
4.2 The student can *design a plan* for collecting data to answer a particular scientific question.
4.3 The student can *collect data* to answer a particular scientific question.
4.4 The student can *evaluate sources of data* to answer a particular scientific question.

Science Practice 5: The student can perform data analysis and evaluation of evidence.

5.1 The student can *analyze data* to identify patterns or relationships.
5.2 The student can *refine observations and measurements* based on data analysis.
5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

Science Practice 6: The student can work with scientific explanations and theories.

6.1 The student can *justify claims with evidence*.
6.2 The student can *construct explanations of phenomena based on evidence* produced through scientific practices.
6.3 The student can *articulate the reasons that scientific explanations and theories are refined or replaced*.
6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.
6.5 The student can *evaluate alternative scientific explanations*.

Science Practice 7: The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains.

7.1 The student can *connect phenomena and models* across spatial and temporal scales.
7.2 The student can *connect concepts* in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Managing Breadth and Increasing Depth

Unit	Managing Breadth	Increasing Depth
Unit 1: Atoms, Reactions, and Stoichiometry: Connecting the Macroscopic World with the Nanoscopic	Chapters 1–4 in Brady and Senese are covered in students' summer assignment. All topics in these chapters are considered to be prior knowledge; they are taught in the prerequisite Chemistry 1 course at Boston Latin School. By including basic atomic structure, mass-mole-atom conversions, measurement, significant figures, uncertainty, and stoichiometry in their summer assignment (with online and face-to-face feedback), we are able to begin the year with challenging stoichiometry problems and inquiry labs.	Because the class is offered as a second-year chemistry course, students already have a basic knowledge of chemistry; this allows AP Chemistry to begin with challenging, thought-provoking laboratories and class work. The green stoichiometry lab calculation (available from the *Journal of Chemical Education* online) requires students to perform an unusual and difficult calculation that has multiple solution approaches, much like future AP Chemistry topics such as kinetics and acid-base equilibrium. Furthermore, class time can be allocated to student-centered activities such as lab-data walks and whiteboarding, where students can simultaneously engage in student-student dialogue and get relevant feedback before the assessment is graded. This allocation of time makes class an experience in which all students can increase their depth of understanding and get feedback from me and their peers.
Unit 2: Reactions Involving Electron Transfer: Single Replacement, Redox, and Electrochemistry	Students no longer need to dedicate class time to learning complicated redox concepts such as Lewis acids and bases and the Nernst equation. Since students no longer need to define oxidizing agent and reducing agent or label positive and negative electrodes, the language related to redox and electrochemical cells is more direct.	As a result of the eliminated topics, more class time can be dedicated to teaching a molecular model of the process of electron transfer during redox, single replacement, and in electrochemical cells. Frequent formative assessment allows me to determine whether students have a complete understanding, and to go back to reteach and provide additional support when necessary.
Unit 3: The Driving Forces: Chemical Energy and Thermodynamics	There has been no significant reduction of learning objectives for these topics.	The Activ physics simulations ask challenging conceptual questions about collision theory, the Maxwell-Boltzman energy distribution, and the first law of thermodynamics. By using the simulations, students can see a molecular, graphical, and algebraic representation of concepts simultaneously. Although the simulations are best done in class, students can complete them independently if they require more time.
Unit 4: Atomic and Molecular Structure: Bonding in Covalent, Ionic, and Metallic Substances	Students no longer need to memorize complicated quantum phenomena such as exceptions to the Aufbau principle, which have historically befuddled students and teachers alike. By developing a consistent model of the nanoscale for ionic, covalent network, and metallic substances, students can focus their analysis on what is similar and what is different at that scale, which results in different macroscale properties.	As a result of reduced coverage of complicated quantum phenomena, a great deal of class time can be dedicated toward modeling the nanoscale and using this model to predict macroscopic behavior. Students can analyze the validity of nanoscale models from simulations and applets using the science practices in the *AP Chemistry Curriculum Framework*.
Unit 5: Particles and Interactions: Gases and Intermolecular Forces	Colligative properties are no longer included in the learning objectives for AP Chemistry, which allows students to focus on the essential properties of matter in the gaseous state and interactions in the liquid and aqueous states.	The elimination of nearly a whole chapter from the syllabus gives students the time to apply their knowledge of gases and intermolecular forces to an inquiry lab, allowing them to design their own procedure and carry out the experiment.
Unit 6: Kinetics: How Fast Does It Go?	Breadth is reduced by no longer requiring students to collect experimental data related to reaction intermediates or derive the Arrhenius equation.	With the elimination of the Arrhenius equation, my students can focus on making connections between kinetics, thermodynamics, and particle representations, rather than on a complicated equation. Students have time to determine the reaction orders themselves, rather than using premade graphs.

Managing Breadth and Increasing Depth *(continued)*

Unit	Managing Breadth	Increasing Depth
Unit 7: General and Solubility Equilibrium: How Far Does It Go?	Because students no longer have to derive equilibrium expressions based upon kinetics, they can dedicate the necessary amount of time to learning about essential equilibrium content through inquiry.	The elimination of the derivation of equilibrium expressions based upon kinetics expressions allows me to spend more time on both guided-inquiry simulations and calculations/problem sets to help my students build understanding.
Unit 8: Acid-Base Equilibrium: Does It Produce or Absorb Protons?	Students no longer have to numerically compute the concentration of each species present in the titration curve for a polyprotic acid. As a result, a great deal of instructional time can be reallocated to critical acid-base equilibrium topics.	Students now have a great deal of lab time in which to examine sophisticated analyses of acid-base equilibrium, such as the first and second derivative methods for determination of an equilibrium constant as a method to interpret titration data and using a titration curve to determine K_a.

Unit 1: Atoms, Reactions, and Stoichiometry: Connecting the Macroscopic World with the Nanoscopic

Laboratory Investigations:

- Green Chemistry Stoichiometry Lab *(guided inquiry)*
- Determination of the Empirical Formula of a Hydrate *(guided inquiry)*
- Qualitative Analysis

Estimated Time:

4 weeks

Essential Questions: ▼ How do we obtain the desired quantities of products from chemical reactions? ▼ Why should chemistry labs be environmentally friendly? ▼ What determines the product of a chemical reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Express the law of conservation of mass quantitatively and qualitatively using symbolic representations and particulate drawings. [LO 1.17, SP 1.5]	**Journal article** Cacciatore and Sevian, "Teaching Lab Report Writing through Inquiry: A Green Chemistry Stoichiometry Experiment for General Chemistry"	**Instructional Activity:** Students design an experiment to determine the percent composition of a mixture of sodium carbonate (inert) and sodium bicarbonate. After carrying out the experiment, they are provided one mock student report to analyze and critique. This allows students to observe multiple approaches to solving this challenging calculation, and to reflect on their own particular approach. It also allows students to observe, interpret, and revise particle-view drawings.
Select and apply mathematical relationships to mass data in order to justify a claim regarding the identity and/or estimated purity of a substance. [LO 1.3, SP 2.2, SP 6.1]		**Formative Assessment:** After lab day, students whiteboard their calculations (i.e., post their work on whiteboards), and then do a data walk where they post sticky notes with "warm" feedback (positive comments) and "cool" feedback (corrections or suggestions for improvement) on other students' work. Students make adjustments to their calculations in their lab reports as a result of the feedback they receive.
		Summative Assessment: Students write formal lab reports in which they detail how their designed procedures allowed them to calculate the percentage composition of the mixture, reflecting on the strength of their percent composition claim based on their experimental evidence. They also critique the strengths and weaknesses of the mock report they were given. Additionally, they explain how this lab meets the criteria for green chemistry.
Design a plan in order to collect data on the synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions. [LO 3.5, SP 2.1, SP 4.2, SP 6.4]		**Instructional Activity:** In small groups, students design an experiment to determine the empirical formula of a hydrate. They write a step-by-step procedure and materials list for their approach.

This is intended to give students feedback on their calculations, and subsequently their lab reports, before the reports are turned in. Comments such as "show your units" and "your calculation is difficult to follow" help students write better reports, and allow me to focus more closely on their understanding of the topics in the reports.

This summative assessment addresses the following essential questions:

- How do we obtain the desired quantities of products from chemical reactions?
- Why should chemistry labs be environmentally friendly?

Hydrated $CuSO_4 \bullet 5H_2O$ is a good choice that is safe to heat. The anhydrous product can be put into solution for other labs. Calcium sulfate hemihydrate ($CaSO_4 \bullet 1/2\ H_2O$) is another safe and interesting possibility.

Essential Questions: ▼ How do we obtain the desired quantities of products from chemical reactions? ▼ Why should chemistry labs be environmentally friendly? ▼ What determines the product of a chemical reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Design a plan in order to collect data on the synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions. [LO 3.5, SP 2.1, SP 4.2, SP 6.4]		**Formative Assessment:** Student pairs peer-evaluate each other's procedures prior to the lab, making at least one change based on their partner's feedback. A data walk takes place after the lab is completed. Students observe other groups' procedures and calculations and post comments on sticky notes regarding experimental design, correctness of calculations, and significant figures.
Use data from synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions. [LO 3.6, SP 2.2, SP 6.1]		**Summative Assessment:** Students write formal lab reports in which they detail how their designed procedures allowed them to calculate the formula of the hydrated compound. Students reflect on the strength of their claims based on the design of their experiments and the validity of the evidence they collected.
Justify the observation that the ratio of the masses of the constituent elements in any pure sample of that compound is always identical on the basis of the atomic molecular theory. [LO 1.1, SP 6.1] Relate quantities (measured mass of substances, volumes of solutions, or volumes and pressures of gases) to identify stoichiometric relationships for a reaction, including situations involving limiting reactants and situations in which the reaction has not gone to completion. [LO 3.4, SP 2.2, SP 5.1, SP 6.4]	Brady and Senese, Chapter 2: "Compounds and Chemical Reactions"; Chapter 3: "Measurement"; and Chapter 4: "The Mole: Connecting the Macroscopic and Molecular Worlds"	**Instructional Activity:** Students perform stoichiometry calculations in small groups. The calculations involve limiting reactants, percent composition, empirical formulas, and combustion analyses. Some problems involve students drawing and interpreting particle drawings. Thinking It Through problems 19 and 20 from Chapter 4 explicitly require students to draw symbolic representations of limiting reactant problems.
		Formative Assessment: Students calculate the final mass produced by a three-step chemical reaction, in which each step has a 90 percent yield. This multistep calculation is done as a whole class, and one student acts as a designated record keeper who gathers ideas and records information on the board. The entire class is assessed for the performance over the course of the period based upon class participation and correct stoichiometry calculations.

This can happen face-to-face with groups exchanging their procedures in class, or online with groups sharing Google Docs and posting comments. Students modify their calculations in their lab reports as a result of the feedback that they receive from their peers.

This summative assessment addresses the essential question, How do we obtain the desired quantities of products from chemical reactions?

Students read the chapter and take five pages of Cornell notes prior to the instructional activities in class. This prereading strategy is employed throughout the year.

I provide feedback about which steps were solved correctly and which were not. If the class does not complete the entire calculation correctly, I assign review problems related to percent yield for homework and go over them in class the next day.

Essential Questions: ▼ How do we obtain the desired quantities of products from chemical reactions? ▼ Why should chemistry labs be environmentally friendly? ▼ What determines the product of a chemical reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Express the law of conservation of mass quantitatively and qualitatively using symbolic representations and particulate drawings. [LO 1.17, SP 1.5] Translate an observed chemical change into a balanced chemical equation and justify the choice of equation type (molecular, ionic, or net ionic) in terms of utility for the given circumstances. [LO 3.2, SP 1.5, SP 7.1]	Hague and Smith, *The Ultimate Chemical Equations Handbook* Brady and Senese, Chapter 5: “Reactions Between Ions in Aqueous Solutions”	**Instructional Activity:** Students complete exercises 9.1, 9.2, 9.3, and 10.1 from *The Ultimate Chemical Equations Handbook* and review the solutions on whiteboards.
		Formative Assessment: I give students two quizzes. For one quiz, students can self-differentiate by content and take level 1 (fundamental), level 2 (challenging), or level 3 (AP level). The choice and the results help me select review groups for the next class. The second quiz is meant to be passed by all students prior to moving on. Students can request a “review quiz” as well.
Predict properties of substances based on their chemical formulas, and provide explanations of their properties based on particle views. [LO 2.1, SP 6.4, SP 7.1]	Hostage and Fossett, Experiment 1: “An Introduction to Qualitative Analysis”	**Instructional Activity:** Students perform a qualitative analysis experiment in which they identify solutions through mixing vials in a QA series.
Translate among macroscopic observations of change, chemical equations, and particle views. [LO 3.1, SP 1.5, SP 7.1]		**Summative Assessment:** Students write formal lab reports in which they justify their predictions for the net ionic equations that occur upon mixing and explain what is happening to the particles on the nanoscale when a net ionic reaction occurs. This enables students to use a representation to analyze and identify the unknowns qualitatively, and explain what makes the reaction occur.
		Summative Assessment: I give students a unit exam, in which they perform calculations, write explanations, and illustrate nanoscale views regarding chemical reactions. Many calculations involve follow-up questions in which students justify their use of calculations and models.

Although The Ultimate Chemical Equations Handbook *is aligned with the pre-2006 style of reactions (Question 4) from the AP Exam, the selected exercises are excellent for students to use to practice and master net ionic reactions and metathesis reactions.*

Students who do not pass level 1 or level 2 quizzes are assigned review problems and encouraged to attend after-school review sessions for individual feedback and practice.

In this iteration of qualitative analysis, students are provided with unknown ionic solutions that can only be mixed with one another in a well plate.

This summative assessment addresses the essential question, What determines the product of a chemical reaction?

The unit exam is administered in two parts. Part 1 contains three short-answer questions with multiple parts each. Part 2 contains 25 calculator-free multiple-choice questions. This summative assessment addresses the following essential questions:

- How do we obtain the desired quantities of products from chemical reactions?
- What determines the product of a chemical reaction?

Unit 2: Reactions Involving Electron Transfer: Single Replacement, Redox, and Electrochemistry

Laboratory Investigations:

- Analysis by Redox Titration
- Exploring Electrochemistry *(guided inquiry)*

Estimated Time:

4 weeks

Essential Questions: ▼ How can studying reactions involving electron transfer help us better understand our technologies? ▼ What are the costs and benefits of using disposable batteries? ▼ Why do only some substances react when mixed?

Learning Objectives	Materials	Instructional Activities and Assessments
Translate among macroscopic observations of change, chemical equations, and particle views. [LO 3.1, SP 1.5, SP 7.1] Identify redox reactions and justify the identification in terms of electron transfer. [LO 3.8 , SP 6.1]	**Web** "Metals in Aqueous Solutions" "Metal/Metal Ion Reactions: A Laboratory Simulation"	**Instructional Activity:** Students explore a series of single replacement reactions, some of which occur, others of which do not. Students draw all ions and solids at the nanoscale for all reactions that *do* occur. Students ultimately list all metals in order of their activity in these reactions.
		Formative Assessment: Students are provided with several 1 molar solutions and a piece of aluminum and asked to select a solution that would react to coat the Al. Students who select incorrect solutions go back and revisit the simulation.
Identify redox reactions and justify the identification in terms of electron transfer. [LO 3.8 , SP 6.1] Apply conservation of atoms to the rearrangement of atoms in various processes. [LO 1.18, SP 1.4]	Brady and Senese, Chapter 6: "Oxidation-Reduction Reactions" and Chapter 21: "Electrochemistry" Hague and Smith, *The Ultimate Chemical Equations Handbook*	**Instructional Activity:** Students balance redox reactions using the ion electron method. For one balanced chemical equation, students draw the reducing agent and the oxidizing agent and show electron transfer between them.
		Formative Assessment: Students take a quiz that asks them to balance a redox equation, identify the chemical species being reduced and the chemical species being oxidized, and illustrate the direction of electron flow.

This simulation is excellent because it allows students to zoom in and see the oxidation-reduction processes, and then zoom back out and see the macroscopic behavior.

Students reflect on the activity in claims, evidence, reasoning format (using Science Practice 6 to justify claims with evidence). These reflections inform the feedback that I provide the students.

For more background on using claims, evidence, and reasoning consult Chapter 11 of Science as Inquiry in the Secondary Setting, *edited by Julie Luft, Randy L. Bell, and Julie Gess-Newsome.*

Students can base this diagram on what they observed in the single replacement activity.

Because this is a required skill to understand electrochemistry and redox stoichiometry, this formative assessment is a "bar" that all students must overcome. Students who do not pass the review receive individual assistance in an extra help session and then take additional, similar quizzes until they demonstrate proficiency.

Essential Questions: ▼ How can studying reactions involving electron transfer help us better understand our technologies? ▼ What are the costs and benefits of using disposable batteries? ▼ Why do only some substances react when mixed?

Learning Objectives	Materials	Instructional Activities and Assessments
Translate an observed chemical change into a balanced chemical equation and justify the choice of equation type (molecular, ionic, or net ionic) in terms of utility for the given circumstances. [LO 3.2, SP 1.5, SP 7.1] Use stoichiometric calculations to predict the results of performing a reaction in the laboratory and/or to analyze deviations from the expected results. [LO 3.3, SP 2.2, SP 5.1] Connect the number of particles, moles, mass, and volume of substances to one another, both qualitatively and quantitatively. [LO 1.4, SP 7.1] Design and/or interpret the results of an experiment involving a redox titration. [LO 3.9, SP 4.2, SP 5.1]	Hostage and Fossett: Experiment 9: “Analysis by Redox Titration”	**Instructional Activity:** Students carry out a redox titration lab using potassium permanganate as an oxidizing agent. In the first part, students standardize their $KMnO_4$ using ferrous ammonium sulfate standard under acidic conditions. In the second part, students use this standardized $KMnO_4$ solution to answer an inquiry. Possibilities are to find the mass percent of iron in a consumer iron supplement, or to determine how much an old bottle of hydrogen peroxide has decomposed. Students use their precision or percent deviation to state their confidence in their accuracy.
		Summative Assessment: Students write a formal laboratory report in which they analyze the percent deviation and subsequent precision for their standardization trials and use that as a predictor for the accuracy of their results in the second experiment of their own design. Both parts of the lab require students to perform stoichiometric calculations. Students discuss the theory of redox in their conclusions, including what is happening to the electrons on the nanoscale. They also list what they have learned from the experiment and perform error analyses of their previous calculations.

Supplements will indicate their percentage iron content (as iron II sulfate) on the package. “Drugstore” peroxide is 3 percent, but will vary to the hundredths place or thousandths place in the determination. The peroxide will decompose noticeably if the bottle is left open overnight.

If the instructor makes one large batch of $KMnO_4$*, it is easy to check students' accuracy with standardization and the follow-up experiment.*

This summative assessment addresses the essential question, Why do only some substances react when mixed? *Lab performance is one of the major areas in which AP Chemistry students are assessed. The three-paragraph conclusion in the lab report is one of the major indicators of understanding for my classes.*

Unit 2: Reactions Involving Electron Transfer: Single Replacement, Redox, and Electrochemistry

(continued)

Essential Questions: ▼ How can studying reactions involving electron transfer help us better understand our technologies? ▼ What are the costs and benefits of using disposable batteries? ▼ Why do only some substances react when mixed?

Learning Objectives	Materials	Instructional Activities and Assessments
Analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions. [LO 3.13, SP 5.1]	**Web** "Voltic Cell"	**Instructional Activity:** Students are presented with the electrochemical cell animation. As a group, they determine what conditions must be present to make the cell function based on voltage data and nanoscale animations of redox reactions. To process the activity, they list the solutions and metals that make electrons flow in the cell.
		Formative Assessment: Students are given a quiz in which they identify all parts of an electrochemical cell and write out the oxidation, reduction, and net ionic reactions in the functioning cell.
	Hostage and Fossett: Experiment 17: "Exploring Electrochemistry"	**Instructional Activity:** Students construct a simple Daniel cell in a well plate. They predict the cell voltage, and then measure the voltage generated and determine whether the behavior matches their predictions. Students also construct several concentration cells to determine the effects of concentration changes on voltage.
		Summative Assessment: Students write formal lab reports in which they identify the redox reactions occurring in the Daniel cell. Students discuss the theory of redox and galvanic cells in their conclusion, including what is happening to the electrons and ions on the nanoscale. They also list what they have learned from the experiment, and perform error analyses of their previous calculations.
Make qualitative or quantitative predictions about galvanic or electrolytic reactions based on half-cell reactions and potentials and/or Faraday's laws. [LO 3.12, SP 2.2, SP 2.3, SP 6.4]	Brady and Senese, Chapter 6: "Oxidation-Reduction Reactions" and Chapter 21: "Electrochemistry"	**Formative Assessment:** Students answer formative assessment questions in a flipped lecture. They have already read and taken Cornell notes on the electrochemistry chapter in their textbooks. The "lecture" is a series of multiple-choice questions, presented on slides, designed to identify misconceptions and force students to defend their choices.
		Summative Assessment: Students take a unit exam that includes multiple-choice and short-answer questions about oxidation-reduction, galvanic cells, electrolytic cells, and redox stoichiometry.

Students who do not pass the quiz receive individual instruction, then review the simulation and revise their quizzes with the correct reactions and parts.

This summative assessment addresses the essential question, What are the costs and benefits of using disposable batteries?

The "flipped" format makes the lecture student centered and informs my decisions about allocation of instructional time to topics.

This summative assessment addresses the essential question, How can studying reactions involving electron transfer help us better understand our technologies?

Unit 3:

The Driving Forces: Chemical Energy and Thermodynamics

Laboratory Investigations:

- Heat Capacity of a Coffee Cup Calorimeter
- Hess's Law: Determining the Enthalpy of a Reaction

Estimated Time:

4 weeks

Essential Questions: ▼ How are energetic changes in chemical reactions represented? ▼ Why do some reactions occur without any intervention, whereas others require a great deal of outside intervention?

Learning Objectives	Materials	Instructional Activities and Assessments
Draw qualitative and quantitative connections between the reaction enthalpy and the energies involved in the breaking and formation of chemical bonds. [LO 5.8, SP 2.3, SP 7.1, SP 7.2]	Brady and Senese, Chapter 7: "Energy and Chemical Change: Breaking and Making Bonds"	**Instructional Activity:** Flipped lecture, geared toward challenging misconceptions about heat vs. temperature, reaction coordinates and bond formation/breaking, PV work, and the laws of thermodynamics.
		Formative Assessment: Students answer the following questions regarding the first law of thermodynamics: *What does it mean, how do we know, why do we believe it is science,* and *why should we care?*
Relate temperature to the motions of particles, either via particulate representations, such as drawings of particles with arrows indicating velocities, and/or via representations of average kinetic energy and distribution of kinetic energies of the particles, such as plots of the Maxwell-Boltzmann distribution. [LO 5.2, SP 1.1, SP 1.4, SP 7.1] Generate explanations or make predictions about the transfer of thermal energy between systems based on this transfer being due to a kinetic energy transfer between systems arising from molecular collisions. [LO 5.3, SP 7.1]	**Web** "Maxwell-Boltzman Distribution: Conceptual Analysis"	**Instructional Activity:** Students explore a conceptual analysis of the Maxwell-Boltzman distribution and the first law of thermodynamics by performing a simulation, answering guiding questions, and performing calculations.
Use conservation of energy to relate the magnitudes of the energy changes occurring in two or more interacting systems, including identification of the systems, the type (heat versus work), or the direction of energy flow. [LO 5.4, SP 1.4, SP 2.2, *connects to* 5.B.1, 5.B.2]	Stacy, *Living by Chemistry*, Unit 5, Lesson 3: "Point of View: First and Second Laws"	**Instructional Activity:** On a worksheet, students draw arrows representing heat flow between the system and the surroundings for reactions that do and do not involve work.

A follow-up class discussion is held the next day, during which I determine whether students understand the difference between heat and internal energy and the ways that a system's internal energy can change. If they do not demonstrate strong understanding of these concepts, I reteach the first law.

This simulation-based "problem set" includes excellent guiding questions to help students make sense of the distribution. Completing the simulations will take one day, and discussion will take one day.

The Driving Forces: Chemical Energy and Thermodynamics

(continued)

Essential Questions: ▼ How are energetic changes in chemical reactions represented? ▼ Why do some reactions occur without any intervention, whereas others require a great deal of outside intervention?

Learning Objectives	Materials	Instructional Activities and Assessments
Interpret observations regarding macroscopic energy changes associated with a reaction or process to generate a relevant symbolic and/or graphical representation of the energy changes. [LO 3.11, SP 1.5, SP 4.4]		**Formative Assessment:** Students draw energy bar graphs for the same situations as in the previous activity, illustrating whether heat flow, work, or both are involved in energetic transitions.
Design and/or interpret the results of an experiment in which calorimetry is used to determine the change in enthalpy of a chemical process (heating/cooling, phase transition, or chemical reaction) at constant pressure. [LO 5.7, SP 4.2, SP 5.1, SP 6.4]	Hostage and Fossett, Experiment 4: "Hess's Law: Determining the Enthalpy Change of a Reaction"	**Instructional Activity:** In small groups, students mix hot and cold water in a coffee cup system and use the difference in temperature change to determine the heat capacity of the calorimeter.
		Formative Assessment: Groups compare results from the previous activity as a class. There are several possibilities for how this may be conducted. Consider having students choose the group with the best precision or with the most convincing argument. Or you may decide to use the weighted average of the groups' results. Since there is no published value (for individual brands) for students to compare to, this activity provides a good opportunity to discuss experimental methods and precision. Students can also carry out a data walk and peer-assess calculations. The class democratically determines the best-supported heat capacity value to use. Students also draw energy bar graphs for the hot and cold water mixing.
		Instructional Activity: Students use two reactions and their calorimeters' heat capacity to calculate the heat of formation of MgO using Hess's law.
		Summative Assessment: Students write formal lab reports in which the results of their calorimetry experiments are used to determine the enthalpy of formation for this chemical process. Students discuss the theory of calorimetry in their conclusions. They also list what they have learned from the experiment, and perform error analyses of their calculations.

Students review their bar graphs on whiteboards and come to a consensus about the correct graphs as a class. If students cannot come to the correct consensus, I reteach energy bar graphs and assign a different problem for students to complete.

Generally, polystyrene-based coffee cups have a heat capacity between 20–40 J/degrees C.

I circulate among the students while they compare and discuss their results, asking probing questions and providing constructive feedback. Students make adjustments to the calculations in their lab reports as a result of the feedback that they receive from their peers.

This summative assessment addresses the essential question, How are energetic changes in chemical reactions represented? *This is another opportunity for students to draw nanoscale representations detailing how the behavior of ions in solution accounts for their macroscale observations, as mentioned in Learning Objective 3.11.*

The Driving Forces: Chemical Energy and Thermodynamics

(continued)

Essential Questions: ▼ How are energetic changes in chemical reactions represented? ▼ Why do some reactions occur without any intervention, whereas others require a great deal of outside intervention?

Learning Objectives	Materials	Instructional Activities and Assessments
Use representations and models to predict the sign and relative magnitude of the entropy change associated with chemical or physical processes. [LO 5.12, SP 1.4]	Brady and Senese, Chapter 20: "Thermodynamics" DeWane, *AP Chemistry: 2007–2008 Professional Development Workshop Materials: Special Focus: Thermochemistry*	**Instructional Activity:** Flipped lecture, in which students discuss and answer multiple-choice questions geared toward identifying misconceptions about heat, temperature, PV work, and the laws of thermodynamics.
Use calculations or estimations to relate changes associated with heating/cooling a substance to the heat capacity, relate energy changes associated with a phase transition to the enthalpy of fusion/vaporization, relate energy changes associated with a chemical reaction to the enthalpy of the reaction, and relate energy changes to PΔV work. [LO 5.6, SP 2.2, SP 2.3] Predict whether or not a physical or chemical process is thermodynamically favored by determination of (either quantitatively or qualitatively) the signs of both $\Delta H°$ and $\Delta S°$, and calculation or estimation of $\Delta G°$ when needed. [LO 5.13, SP 2.2, SP 2.3, SP 6.4, *connects to* 5.E.3] Determine whether a chemical or physical process is thermodynamically favorable by calculating the change in standard Gibbs free energy. [LO 5.14, SP 2.2, *connects to* 5.E.2]		**Instructional Activity:** In small groups, students perform thermodynamics calculations, using a teacher-developed set of problems involving qualitative predictions and quantitative calculations related to enthalpy, entropy, and Gibbs free energy. Groups focus on how they select, apply, and check their mathematical routines to solve problems.

There are approximately 10 multiple-part problems in the set, which involve enthalpy, formation reactions, entropy, and free energy equations.

Essential Questions: ▼ How are energetic changes in chemical reactions represented? ▼ Why do some reactions occur without any intervention, whereas others require a great deal of outside intervention?

Learning Objectives	Materials	Instructional Activities and Assessments
		Summative Assessment: Students take a unit exam encompassing redox, electrochemistry, chemical energy, and thermodynamics. On this exam, students perform calculations, write explanations, and illustrate nanoscale views for redox in solution, single replacement, and batteries. Students model energetic changes qualitatively, algebraically, and graphically. Many calculations involve follow-up questions in which students justify their use of calculations and models. This is a two-day exam, consisting of multiple-choice questions, short-answer questions, and calculations. By completing this exam, students demonstrate their level of proficiency and understanding of how to represent energetic changes in chemical reactions.

This summative assessment addresses the essential question, Why do some reactions occur without any intervention, whereas others require a great deal of outside intervention?

Unit 4:

Atomic and Molecular Structure: Bonding in Covalent, Ionic, and Metallic Substances

Laboratory Investigations:

- Exploring Quantum Phenomena with Gas Discharge Tubes *(guided inquiry)*
- Using PhET to Study Five Models of the Hydrogen Atom

Estimated Time:

4 weeks

Essential Questions: ▼ What are the implications if the quantum model is inaccurate? ▼ What can and can't we know about a chemical bond? ▼ Why do scientists focus on modeling the nanoscale based upon macroscale properties?

Learning Objectives	Materials	Instructional Activities and Assessments
Explain why a given set of data suggests, or does not suggest, the need to refine the atomic model from a classical shell model with the quantum mechanical model. [LO 1.12, SP 6.3]	Brady and Senese, Chapter 8: "The Quantum Mechanical Atom"	**Instructional Activity:** Students perform self-directed research on teacher-selected topics including electron diffraction, the photoelectric effect, the Bohr description of the atom, quantum numbers, electron configurations, the Aufbau principle, Hunds' rule, the Pauli exclusion principle, and the Heisenberg uncertainty principle. Students then jigsaw their research in groups of seven. I have them use simple poster board to present their research to the other group members, who take summary notes.
Analyze data relating to electron energies for patterns and relationships. [LO 1.6, SP 5.1] Predict and/or justify trends in atomic properties based on location on the periodic table and/or the shell model. [LO 1.9, SP 6.4]	**Web** WebElements	**Instructional Activity:** Students make comparisons of periodic properties of pairs of elements, including atomic radius, ionic radius, electron affinity, and first ionization energy, and justify them based upon the electron configurations of the respective elements and the energy well model. Students check their answers on WebElements.
Justify with evidence the arrangement of the periodic table and apply periodic properties to chemical reactivity. [LO 1.10, SP 6.1] Analyze data, based on periodicity and the properties of binary compounds, to identify patterns and generate hypotheses related to the molecular design of compounds for which data are not supplied. [LO 1.11, SP 3.1, SP 5.1]		**Instructional Activity:** Students compare the strength of halogen acids and relate this strength to electron configuration and periodicity.
	Web WebElements	**Formative Assessment:** Students complete a quiz comparing periodic properties of two new elements and making inferences about relative periodic table position based on reactivity and bond length data. Students who do not pass the quiz go back and revise their answers based on the data available on the WebElements website.

A jigsaw is an activity in which each student in a group becomes an expert on one topic, consults with an "expert" group made up of other students who were assigned the same topic, and then presents that topic back to the other members of his or her original group.

For example, students could compare sodium and potassium, carbon and nitrogen, or oxygen and fluorine.

I use students' performance on this assessment to make decisions about next instructional steps.

Atomic and Molecular Structure: Bonding in Covalent, Ionic, and Metallic Substances *(continued)*

Essential Questions: ▼ What are the implications if the quantum model is inaccurate? ▼ What can and can't we know about a chemical bond? ▼ Why do scientists focus on modeling the nanoscale based upon macroscale properties?

Learning Objectives	Materials	Instructional Activities and Assessments
Create a representation of an ionic solid that shows essential characteristics of the structure and interactions present in the substance. [LO 2.23, SP1.1] Explain a representation that connects properties of an ionic solid to its structural attributes and to the interactions present at the atomic level. [LO 2.24, SP 1.1, SP 6.2, SP 7.1] Create visual representations of ionic substances that connect the microscopic structure to macroscopic properties, and/or use representations to connect the microscopic structure to macroscopic properties (e.g., boiling point, solubility, hardness, brittleness, low volatility, lack of malleability, ductility, or conductivity). [LO 2.19, SP 1.1, SP 1.4, SP 7.1, *connects to* 2.D.1, 2.D.2]	Brady and Senese, Chapter 13: "Structures, Properties, and Applications of Solids" **Web** "Merging Two NaCl Crystals" "Molecular Dynamics Simulation of Sodium Chloride"	**Instructional Activity:** Students observe the two simulations and construct a model of ionic solids. Students list how interactions at the atomic level account for macroscopic properties. Pairs of students draw a model of a particular salt and explain its bond strength, hardness, and solubility relative to other salts based upon Coulomb's law.
Predict the type of bonding present between two atoms in a binary compound based on position in the periodic table and the electronegativity of the elements. [LO 2.17, SP 6.4]	**Web** "Bonding" (using Spartan density maps) Bonding tutorial questions	**Instructional Activity:** Students make predictions and test them in order to determine the important factors for the formation of an ionic, polar covalent, or nonpolar covalent bond. They can do so by summarizing their findings without explicit questions, or by completing questions that accompany the simulation.
Rank and justify the ranking of bond polarity on the basis of the locations of the bonded atoms in the periodic table. [LO 2.18, SP 6.1]		**Formative Assessment:** On whiteboards, students make predictions about polarity and ionic/covalent character based on periodic position.

A possible extension could include drawing the cations and anions in solution and a discussion of the comparative strength of ion-ion interactions and ion-dipole interactions.

If students are unable to complete this and explain their rationale, they are directed to attend extra help sessions and review their Cornell notes from Chapter 13.

Students give peer feedback on one another's predictions until a class consensus is reached. If class consensus is incomplete or incorrect, I go back and reteach the material using supplemental visuals of the bonding continuum.

Essential Questions: ▼ What are the implications if the quantum model is inaccurate? ▼ What can and can't we know about a chemical bond? ▼ Why do scientists focus on modeling the nanoscale based upon macroscale properties?

Learning Objectives	Materials	Instructional Activities and Assessments
Explain how a bonding model involving delocalized electrons is consistent with macroscopic properties of metals (e.g., conductivity, malleability, ductility, and low volatility) and the shell model of the atom. [LO 2.20, SP 6.2, SP 7.1, *connects to* 2.D.2] Compare the properties of metal alloys with their constituent elements to determine if an alloy has formed, identify the type of alloy formed, and explain the differences in properties using particulate level reasoning. [LO 2.25, SP 1.4, SP 7.2] Use the electron sea model of metallic bonding to predict or make claims about the macroscopic properties of metals or alloys. [LO 2.26, SP 6.4, SP 7.1]	Brady and Senese, Chapter 13: "Structures, Properties, and Applications of Solids" **Web** "Metallic Bonding and the Properties of Metals" "Metallic Bonding" "Metallic Alloy"	**Instructional Activity:** Based on Internet and text research, students create visual models of metallic bonds in both pure substances and alloys that incorporate delocalized electrons in an electron sea model. Students defend how their models would look in a malleable or ductile situation.
Create a representation of a metallic solid that shows essential characteristics of the structure and interactions present in the substance. [LO 2.27, SP 1.1] Explain a representation that connects properties of a metallic solid to its structural attributes and to the interactions present at the atomic level. [LO 2.28, SP 1.1, SP 6.2, SP 7.1]		**Formative Assessment:** Students give presentations on a fictional alloy that they have designed, with the rest of the class serving as a mock panel of investors. In their presentations, students compare their alloy to an inferior alloy, and share a visual model of their alloy that shows general features (e.g., the electron sea model of metallic bonds) and specific features (e.g., the interactions within this particular alloy and macroscopic properties that result).
		Summative Assessment: Students take a unit exam encompassing bonding in metallic, covalent, and ionic substances. On this exam, students perform calculations, write explanations, and illustrate nanoscale views for compounds of all types.

This could be done in pairs or in small groups.

Students who do not give adequate presentations attend an extra help session where they receive individual instruction about alloys. They also complete supplemental reading in their textbooks and write a one-page summary of changes they would make to their presentations.

This summative assessment addresses the following essential questions:
- What can and can't we know about a chemical bond?
- Why do scientists focus on modeling the nanoscale based upon macroscale properties?

Essential Questions: ▼ What are the implications if the quantum model is inaccurate? ▼ What can and can't we know about a chemical bond? ▼ Why do scientists focus on modeling the nanoscale based upon macroscale properties?

Learning Objectives	Materials	Instructional Activities and Assessments
Explain why a given set of data suggests, or does not suggest, the need to refine the atomic model from a classical shell model with the quantum mechanical model. [LO 1.12, SP 6.3] Given information about a particular model of the atom, determine if the model is consistent with specified evidence. [LO 1.13, SP 5.3] Translate among macroscopic observations of change, chemical equations, and particle views. [LO 3.1, SP 1.5, SP 7.1]	**Web** "Models of the Hydrogen Atom"	**Instructional Activity:** Students decide what data to collect, and then compare the emission spectra of hydrogen, helium, neon, and argon to a continuous light spectrum. Students complete a series of guided-inquiry questions using the PhET "Models of the Hydrogen Atom" simulation. They observe what occurs in the simulation, and match it up with evidence that they observed from gas emission tubes. Students explain which behaviors are and are not consistent with observed macroscopic properties of gas emissions.
		Summative Assessment: Students make formal presentations in which they compare the models of the hydrogen atom and discuss evidence that supports each. Specific focus is devoted to which model is adequate to explain spectral line observations.

To collect qualitative data, a simple diffraction grating will allow students to observe the difference between the continuous spectrum of sunlight and the discrete spectrum of emission tubes (in a dark room). Analyses could include the billiard ball, solar system, Bohr, standing wave, and Schrödinger models. This activity provides students with the explicit opportunity to demonstrate proficiency with Learning Objective 1.13.

This summative assessment addresses the essential question, What are the implications if the quantum model is inaccurate?

Unit 5: Particles and Interactions: Gases and Intermolecular Forces

Laboratory Investigations:

- Chromatography of a Popular Consumer Beverage
- Molar Volume of a Gas
- Identifying the Fluid in a Lighter *(inquiry)*

Estimated Time:

3.5 weeks

Essential Questions: ▼ What complications can arise in scientific investigations based on making assumptions about gas behavior? ▼ Why do physical data, such as boiling point, sometimes deviate from predictions? ▼ Which interactions on the nanoscale best explain behavior on the macroscale?

Learning Objectives	Materials	Instructional Activities and Assessments
Use KMT and concepts of intermolecular forces to make predictions about the macroscopic properties of gases, including both ideal and nonideal behaviors. [LO 2.4, SP 1.4, SP 6.4] Relate temperature to the motions of particles, either via particulate representations, such as drawings of particles with arrows indicating velocities, and/or via representations of average kinetic energy and distribution of kinetic energies of the particles, such as plots of the Maxwell-Boltzmann distribution. [LO 5.2, SP 1.1, SP 1.4, SP 7.1]	Brady and Senese, Chapter 11: “Properties of Gases” **Web** “State Variables and Ideal Gas Law”	**Instructional Activity** Students complete the “State Variables and Ideal Gas Law” simulation. They answer questions and complete calculations involving collisions, Boyle’s law, Charles’ law, and Gay-Lussac’s law. At the end of the simulation, students perform calculations to determine the pressure at each point in a Carnot cycle. Simulations contain a particle view, an animation, a graph showing variable changes, and a bar graph showing the first law of thermodynamics.
Refine multiple representations of a sample of matter in the gas phase to accurately represent the effect of changes in macroscopic properties on the sample. [LO 2.5, SP 1.3, SP 6.4, SP 7.2]		**Formative Assessment:** Students design a three- to four-step combustion-engine cycle for their classmates to calculate. At each step, the cycle must incorporate a particle view of gas behavior, a bar graph of heat flow and work, and a calculation of pressure using the ideal gas law.
Relate quantities (measured mass of substances, volumes of solutions, or volumes and pressures of gases) to identify stoichiometric relationships for a reaction, including situations involving limiting reactants and situations in which the reaction has not gone to completion. [LO 3.4, SP 2.2, SP 5.1, SP 6.4]		**Instructional Activity:** Students complete an experiment in which they react magnesium metal with hydrochloric acid and measure the volume of hydrogen gas generated. Students determine the limiting reactant in the reaction.
		Summative Assessment: Students write formal lab reports in which they calculate the molar volume of dry hydrogen gas, determine the limiting reactant in the reaction, and speculate on the most prominent sources of error.

A possible extension could include drawing the cations and anions in solution and a discussion of the comparative strength of ion-ion interactions and ion-dipole interactions.

All student-designed and student-calculated solutions are compared to instructor solutions. If a student has an incorrect answer, I reteach the material and they revise their calculation.

This summative assessment addresses the essential question, What complications can arise in scientific investigations based on making assumptions about gas behavior?

Essential Questions: ▼ What complications can arise in scientific investigations based on making assumptions about gas behavior? ▼ Why do physical data, such as boiling point, sometimes deviate from predictions? ▼ Which interactions on the nanoscale best explain behavior on the macroscale?

Learning Objectives	Materials	Instructional Activities and Assessments
Apply mathematical relationships or estimation to determine macroscopic variables for ideal gases. [LO 2.6 , SP 2.2, SP 2.3]		**Instructional Activity:** Students design an experiment in which they apply mathematical relationships in the ideal gas law to determine the hydrocarbon present as lighter fluid.
		Summative Assessment: Students write formal lab reports in which they identify the lighter fluid and show calculations to support their determination. This requires students to apply a mathematical relationship to determine the macroscopic behavior. Students write their conclusions in claims, evidence, reasoning format.
Design and/or interpret the results of a separation experiment (filtration, paper chromatography, column chromatography, or distillation) in terms of the relative strength of interactions among and between the components. [LO 2.10, SP 4.2, SP 5.1, SP 6.4]	Hostage and Fossett, Experiment 15: "Chromatography of a Popular Consumer Beverage"	**Instructional Activity:** Students perform paper chromatography on several Kool-Aid samples.
Explain how solutes can be separated by chromatography based on intermolecular interactions. [LO 2.7, SP 6.2] Draw and/or interpret representations of solutions that show the interactions between the solute and solvent. [LO 2.8, SP 1.1, SP 1.2, SP 6.4]		**Summative Assessment:** Students write formal lab reports, including three-paragraph conclusions that address theory, what the student learned, and sources of error. In the theory section, students explain chromatography by drawing molecules in the beverage interacting with each other and the paper during the mobile phase. Students explain whether the molecule-molecule or molecule-paper forces are stronger based upon their drawings.

Consider having students submit their designs as Google Docs and post comments remotely to allow them to peer-evaluate their experimental designs and thereby perfect them in a collaborative setting.

This summative assessment addresses the essential question, What complications can arise in scientific investigations based on making assumptions about gas behavior?

Grape, cherry, and orange tend to provide good results. Individual packets work well for lab groups.

This summative assessment addresses the essential question, Which interactions on the nanoscale best explain behavior on the macroscale?

Essential Questions: ▼ What complications can arise in scientific investigations based on making assumptions about gas behavior? ▼ Why do physical data, such as boiling point, sometimes deviate from predictions? ▼ Which interactions on the nanoscale best explain behavior on the macroscale?

Learning Objectives	Materials	Instructional Activities and Assessments
Predict properties of substances based on their chemical formulas, and provide explanations of their properties based on particle views. [LO 2.1, SP 6.4, SP 7.1] Explain the trends in properties and/or predict properties of samples consisting of particles with no permanent dipole on the basis of London dispersion forces. [LO 2.11, SP 6.2, SP 6.4] Describe the relationships between the structural features of polar molecules and the forces of attraction between the particles. [LO 2.13, SP 1.4, SP 6.4] Explain the properties (phase, vapor pressure, viscosity, etc.) of small and large molecular compounds in terms of the strengths and types of intermolecular forces. [LO 2.16, SP 6.2]	Brady and Senese, Chapter 12: “Intermolecular Attractions and the Properties of Liquids and Solids”	**Instructional Activity:** Students complete an assignment called “Properties of Substances” in which they explain physical properties such as boiling point, melting point, and electrical conductivity based on the identity and relative magnitude of intermolecular forces. Verbal explanations are accompanied by molecular-level diagrams, which display a mechanism for the interactions.
Make claims and/or predictions regarding relative magnitudes of the forces acting within collections of interacting molecules based on the distribution of electrons within the molecules and the types of intermolecular forces through which the molecules interact. [LO 5.9, SP 6.4] Identify the noncovalent interactions within and between large molecules, and/or connect the shape and function of the large molecule to the presence and magnitude of these interactions. [LO 5.11, SP 7.2]		**Formative Assessment:** Students are asked, in small groups, to explain why a solution of sugar water spilled on a table is sticky. Students predict whether sucrose is more or less sticky than glucose, and design a hypothetical experiment to test their hypothesis.

For example, students could show stronger hydrogen bonding between ammonia molecules than phosphine molecules, thus explaining ammonia’s higher boiling point. This could be in the form of an individual quiz, a group quiz, or a class debate.

Students may have the misconception that sugar forms a formal bond with the table. They may also think that sucrose is stickier because it has a higher molar mass. I reteach intermolecular forces, with a special focus on London forces, to groups that fail to correctly explain the phenomena or design an experiment. Following this, I assign them supplemental reading online and have them resubmit a prediction and procedure.

Particles and Interactions: Gases and Intermolecular Forces *(continued)*

Essential Questions: ▼ What complications can arise in scientific investigations based on making assumptions about gas behavior? ▼ Why do physical data, such as boiling point, sometimes deviate from predictions? ▼ Which interactions on the nanoscale best explain behavior on the macroscale?

Learning Objectives	Materials	Instructional Activities and Assessments
Use conservation of energy to relate the magnitudes of the energy changes when two nonreacting substances are mixed or brought into contact with one another. [LO 5.5, SP 2.2, *connects to* 5.B.1, 5.B.2] Create or interpret representations that link the concept of molarity with particle views of solutions. [LO 2.9, SP 1.1, SP 1.4]	Brady and Senese, Chapter 14: "Solutions" **Web** "Salt Solution"	**Instructional Activity:** Students draw molecular representations of solutions that are being diluted by factors of two and factors of 10 for ionic and covalent compounds. Students view an animation of salt dissolving and explain the energetic transformations at each stage.
Qualitatively analyze data regarding real gases to identify deviations from ideal behavior and relate these to molecular interactions. [LO 2.12, SP 5.1, SP 6.5, *connects to* 2.A.2]	Brady and Senese, Chapter 11: "Properties of Gases"	**Instructional Activity:** Students calculate the real pressure generated by oxygen gas based on the Van der Waals equation and compare this value to the value predicted by the ideal gas law.
		Summative Assessment: Students take a unit exam that requires them to write explanations and illustrate nanoscale views regarding gases, intermolecular forces, and properties of covalent, ionic, and metallic substances. Many calculations involve follow-up questions requiring students to justify their use of calculations and models, especially in cases where physical data deviates from predicted values.

Students should eliminate water from their drawings in order to simplify the representations.

This summative assessment addresses the essential question, Why do physical data, such as boiling point, sometimes deviate from predictions?

Unit 6: Kinetics: How Fast Does It Go?

Laboratory Investigations:

- The Kinetics of a Bleach Reaction
- Kinetics: Differential Rate Laws *(guided inquiry)*
- Kinetics: Integrated Rate Laws

Estimated Time:

4 weeks

Essential Questions: ▼ What potential hazards could arise from ignoring rates of reaction? ▼ How do molecules actually interact during a chemical reaction? ▼ Does a reaction mechanism accurately tell scientists what occurs at the molecular level?

Learning Objectives	Materials	Instructional Activities and Assessments
Analyze concentration vs. time data to determine the rate law for a zeroth-, first-, or second-order reaction. [LO 4.2, SP 5.1, SP 6.4, *connects to* 4.A.3]	**Web** "The Kinetics of a Bleach Reaction"	**Instructional Activity:** Students collect concentration vs. time data for the reaction of food coloring and bleach to determine the order of the bleach reaction.
		Formative Assessment: Students use kinetics data to propose whether green food coloring contains a different-colored molecule or is a mixture of yellow and blue food coloring by examining the peak absorbencies and reaction order of decomposition. This lets me know whether the students can correctly analyze reaction orders.
Design and/or interpret the results of an experiment regarding the factors (i.e., temperature, concentration, surface area) that may influence the rate of a reaction. [LO 4.1, SP 4.2, SP 5.1]	Brady and Senese, Chapter 15: "Kinetics: The Study of Rates of Reaction" Hostage and Fossett, Experiment 13: "Kinetics: Differential and Integrated Rate Laws" (Part A)	**Instructional Activity:** Students design a set of experiments in a guided-inquiry investigation to determine the reaction order for the decomposition of hydrogen peroxide using both a heterogeneous and a homogenous catalyst, based solely on the assumption that all reactants contribute to the reaction as a 0, 1, 2 order reactant or catalyst. The heterogeneous catalyst experiments should vary the amount of peroxide only; the homogeneous catalysts should vary both catalyst and peroxide concentrations.
Evaluate alternative explanations, as expressed by reaction mechanisms, to determine which are consistent with data regarding the overall rate of a reaction, and data that can be used to infer the presence of a reaction intermediate. [LO 4.7, SP 6.5, *connects to* 4.C.1, 4.C.2, 4.C.3] Explain changes in reaction rates arising from the use of acid-base catalysts, surface catalysts, or enzyme catalysts, including selecting appropriate mechanisms with or without the catalyst present. [LO 4.9, SP 6.2, SP 7.2]		**Summative Assessment:** Students write formal laboratory reports in which they use both data sets to determine the reaction order of H_2O_2 decomposition. Students compare potential reaction mechanisms and deduce the presence or lack of a reaction intermediate based upon the students' predicted rate law.

I use this as an introductory activity in my class, but you could have students do an extended study of the mechanism with information about the dyes in food coloring.

Students share claims, evidence, and reasoning on whiteboards and come to a consensus about the mixture. If they come to the incorrect conclusion about the reaction order, I review integrated rate laws and have students reanalyze their data and revise their claims, evidence, and reasoning statements.

Pyrolucite is a good, cheap surface catalyst to use.

This summative assessment addresses the essential question, What potential hazards could arise from ignoring rates of reaction?

Essential Questions: ▼ What potential hazards could arise from ignoring rates of reaction? ▼ How do molecules actually interact during a chemical reaction? ▼ Does a reaction mechanism accurately tell scientists what occurs at the molecular level?

Learning Objectives	Materials	Instructional Activities and Assessments
Connect the half-life of a reaction to the rate constant of a first-order reaction and justify the use of this relation in terms of the reaction being a first-order reaction. [LO 4.3, SP 2.1, SP 2.2]	Hostage and Fossett, Experiment 13: "Kinetics: Differential and Integrated Rate Laws" (Part B)	**Instructional Activity:** Students analyze and graph data from Geiger counter readings of a sample of P-32. Students determine the reaction order based on the analysis of the graph.
		Summative Assessment: Students write formal lab reports in which they calculate the rate constant (*k*), and the half-life of the reaction.
Analyze concentration vs. time data to the rate law for a zeroth-, first-, or second-order reaction. [LO 4.2, SP 5.1, SP 6.4, *connects to* 4.A.3]		**Instructional Activity:** Students graph concentration vs. time, natural logarithm concentration vs. time, and 1/concentration vs. time data for several data sets and use these data sets to determine the reaction order.
		Formative Assessment: Students take a quiz that requires them to determine the reaction order and the value of *k* based upon concentration vs. time, natural logarithm concentration vs. time, and 1/concentration vs. time data.
Use representations of the energy profile for an elementary reaction (from the reactants, through the transition state, to the products) to make qualitative predictions regarding the relative temperature dependence of the reaction rate. [LO 4.6, SP 1.4, SP 6.4]		**Instructional Activity:** Students draw energy profiles for a reaction occurring at a high temperature and a low temperature.
		Formative Assessment: Students draw energy profiles for the same chemical reaction as in the previous activity based on two Maxwell-Boltzman energy diagrams and justify their choices.
Connect the rate law for an elementary reaction to the frequency and success of molecular collisions, including connecting the frequency and success to the order and rate constant, respectively. [LO 4.4, SP 7.1, *connects to* 4.A.3, 4.B.2]	**Web** "Reactions & Rates" "Reaction Mechanisms"	**Instructional Activity:** Students explore what makes a reaction happen by colliding atoms and molecules in an online PhET simulation. Students design experiments with different reactions, concentrations, and temperatures and observe the frequency of effective collisions in each case. Students can also view the tutorial on reaction mechanisms to help them develop their hypotheses to accompany their experimental designs.

The data set is in "rough" format, so students need to make calculations to put the data into concentration-vs.-time format to graph. This can be done by hand or by writing formulas in Excel.

This summative assessment addresses the essential question, What potential hazards could arise from ignoring rates of reaction?

I use data sets from rate law problem sets in our course text.

Question 3 from the 2005B free-response questions is an excellent question to draw upon.

Students who do not pass the quiz attend an after-school help session in which I review how to analyze graphical kinetics data. After the review I give them supplemental problems, which they solve individually and then exchange peer review and feedback.

Students share their predictions on whiteboards and come to a consensus. If the class cannot reach the correct consensus, I reteach the material and have the class revise their energy profiles.

You may consider freezing the screen at the start of the reaction and have students complete their drawings based upon the predicted progression of the reaction.

Essential Questions: ▼ What potential hazards could arise from ignoring rates of reaction? ▼ How do molecules actually interact during a chemical reaction? ▼ Does a reaction mechanism accurately tell scientists what occurs at the molecular level?

Learning Objectives	Materials	Instructional Activities and Assessments
Explain the difference between collisions that convert reactants to products and those that do not in terms of energy distributions and molecular orientation. [LO 4.5, SP 6.2] Translate among reaction energy profile representations, particulate representations, and symbolic representations (chemical equations) of a chemical reaction occurring in the presence and absence of a catalyst. [LO 4.8, SP 1.5]		**Formative Assessment:** Students draw energy profiles and a representation of effective and ineffective collisions based on energy and molecular orientation for a model reaction similar to the one explored in the preceding instructional activity.
		Summative Assessment: Students take a unit exam that requires them to calculate reaction order for reactions based upon graphical and empirical data. Students draw and interpret energy profiles for reactions and explain their results in terms of successful molecular collisions.

Students share their representations on whiteboards, and the class votes on whether the profiles are valid. If the class cannot reach the correct consensus, I reteach the material and have students revise their energy profiles.

This summative assessment relates to the following essential questions:

- How do molecules actually interact during a chemical reaction?
- Does a reaction mechanism accurately tell scientists what occurs at the molecular level?

Unit 7: General and Solubility Equilibrium: How Far Does It Go?

Laboratory Investigations:

- Connecting Solubility, Equilibrium, and Periodicity in a Green Chemistry Situation *(guided inquiry)*

Estimated Time:

4 weeks

Essential Questions: ▼ What economic impacts result from limits in equilibrium yields of industrial products? ▼ How does calcium carbonate solubility in the ocean affect your daily life?

Learning Objectives	Materials	Instructional Activities and Assessments
Given a set of experimental observations regarding physical, chemical, biological, or environmental processes that are reversible, construct an explanation that connects the observations to the reversibility of the underlying chemical reactions or processes. [LO 6.1, SP 6.2] Connect kinetics to equilibrium by using reasoning about equilibrium, such as LeChatelier's principle, to infer the relative rates of the forward and reverse reactions. [LO 6.3, SP 7.2]	Brady and Senese, Chapter 16: "Chemical Equilibrium — General Concepts"	**Instructional Activity:** Students perform a modeling experiment in which they use colored blocks to represent reactants and products in an equilibrium system. They pass the blocks from right to left on a table according to a forward and reverse rate to simulate a system at equilibrium. Students discover that the ratio of the rate constants is a constant value.
Given a manipulation of a chemical reaction or set of reactions (e.g., reversal of reaction or addition of two reactions), determine the effects of that manipulation on *Q* or *K*. [LO 6.2, SP 2.2]		**Instructional Activity:** Students complete a series of calculations of *Q* based on initial concentrations and *K* based on equilibrium concentrations. Students are asked to describe the behavior of the system when *Q* is bigger than, smaller than, and equal to *K*.
Given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, *K*, use the tendency of *Q* to approach *K* to predict and justify the prediction as to whether the reaction will proceed toward products or reactants as equilibrium is approached. [LO 6.4, SP 2.2, SP 6.4]		**Formative Assessment:** Students calculate whether a system is at equilibrium based on concentrations of reactants and products.
Given data (tabular, graphical, etc.) from which the state of a system at equilibrium can be obtained, calculate the equilibrium constant, *K*. [LO 6.5, SP 2.2] For a reversible reaction that has a large or small *K*, determine which chemical species will have very large versus very small concentrations at equilibrium. [LO 6.7, SP 2.2, SP 2.3]		**Instructional Activity:** Students complete a series of calculations in which they determine *K* or equilibrium concentrations based on initial concentrations.

The number of blocks passed from side to side is different for a few rounds, but after a certain point students are passing the same number of blocks from one side to the other; the reaction has come to dynamic equilibrium.

Students who do not successfully complete the assessment attend an after-school review session where I reteach the relationship between Q *and* K*. The students are then given supplemental* Q *vs.* K *problems, which we review together.*

Unit 7: General and Solubility Equilibrium: How Far Does It Go? *(continued)*

Essential Questions: ▼ What economic impacts result from limits in equilibrium yields of industrial products? ▼ How does calcium carbonate solubility in the ocean affect your daily life?

Learning Objectives	Materials	Instructional Activities and Assessments
Given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, *K*, use stoichiometric relationships and the law of mass action (*Q* equals *K* at equilibrium) to determine qualitatively and/or quantitatively the conditions at equilibrium for a system involving a single reversible reaction. [LO 6.6, SP 2.2, SP 6.4]		**Formative Assessment:** Students review their calculations from the previous activity on whiteboards and ask one another questions related to relative concentrations at equilibrium as well as whether reactions favor reactants or products.
Connect LeChatelier's principle to the comparison of *Q* to *K* by explaining the effects of the stress on *Q* and *K*. [LO 6.10, SP 1.4, SP 7.2]		**Instructional Activity:** Students complete a problem set in which they determine how different stressors would shift or not shift an equilibrium system. Students share their answers with the class and discuss how the stresses change *Q*, leading to a shift in order for the reaction to reach *K*.
Use LeChatelier's principle to predict the direction of the shift resulting from various possible stresses on a system at chemical equilibrium. [LO 6.8, SP 1.4, SP 6.4]		**Instructional Activity:** Students complete a PEOE demonstration cycle for a sealed tube of NO_2/N_2O_4 based upon their understanding of LeChatelier's principle.
		Formative Assessment: Students take a quiz about equilibrium reactions and LeChatelier's principle.
Predict the solubility of a salt, or rank the solubility of salts, given the relevant K_{sp} values. [LO 6.21, SP 2.2, SP 2.3, SP 6.4] Interpret data regarding solubility of salts to determine, or rank, the relevant K_{sp} values. [LO 6.22, SP 2.2, SP 2.3, SP 6.4]	Brady and Senese, Chapter 19: "Solubility and Simultaneous Equilibria" **Web** "Salts & Solubility"	**Instructional Activity:** Students complete an open-ended exploration of the PhET simulation in which they deduce the relationship between behavior of the ions in solution and the solubility and K_{sp} of the solute in the simulation.
		Formative Assessment: Students rank salts based on molar solubility, K_{sp}, or other data.

Students give peer feedback on the calculations, and come to a consensus about the solutions. If the correct consensus isn't reached by the class, I reteach mass action expressions and equilibrium concentrations and have students redo their calculations.

Prepare some guiding questions to help students peer-assess. For example, Which direction does equilibrium shift when *Q* is bigger than *K*?

PEOE stands for predict, explain, observe, explain. Using this framework helps to make demonstrations a better learning experience for all students in class by requiring them to explain their predictions, make sense of the outcomes, and reflect upon whether their initial thinking was consistent with the outcome or not.

Students who do not pass the quiz are given supplemental reading online and additional LeChatelier's principle calculations to complete. I then review these additional calculations with the students individually.

If students do not correctly rank the salts, we review the correct ranking and its relationship to K_{sp}*. Students are also given reading online related to solubility and* K_{sp}*.*

General and Solubility Equilibrium: How Far Does It Go? *(continued)*

Essential Questions: ▼ What economic impacts result from limits in equilibrium yields of industrial products? ▼ How does calcium carbonate solubility in the ocean affect your daily life?

Learning Objectives	Materials	Instructional Activities and Assessments
Interpret data regarding the relative solubility of salts in terms of factors (common ions, pH) that influence the solubility. [LO 6.23, SP 5.1, SP 6.4]	**Web** Cacciatore, Amado, and Evans, "Connecting Solubility, Equilibrium, and Periodicity in a Green, Inquiry Experiment for the General Chemistry Laboratory"	**Instructional Activity:** Students titrate three saturated hydroxide solutions to determine the relationship between solubility and periodicity of the cations.
		Summative Assessment: Students complete formal lab reports in which they provide a mechanism for the periodic trend in solubility supported by their data.
Express the equilibrium constant in terms of $\Delta G°$ and RT and use this relationship to estimate the magnitude of K and, consequently, the thermodynamic favorability of the process. [LO 6.25, SP 2.3]	**Web** "Salt Solution"	**Instructional Activity:** Students observe the simulation and describe what is occurring at each stage of the dissolution. They deduce which portions of the dissolution are endothermic and which are exothermic. They also calculate the Gibbs free energy for the reaction based upon K at room temperature.
Analyze the enthalpic and entropic changes associated with the dissolution of a salt, using particulate level interactions and representations. [LO 6.24, SP 1.4, SP 7.1, *connects to* 5.E]		**Formative Assessment:** Students draw a reaction coordinate for the dissolution of ammonium chloride at room temperature and indicate the direction of heat flow between the system and the surroundings.
		Summative Assessment: Students take a unit exam in which they complete general and solubility equilibrium calculations, interpret reaction coordinates, and explain the relationship between the equilibrium constant of a reaction and product yield. Students answer follow-up questions related to LeChatelier's principle.

Students can infer how this is related to the impact of ocean warming and acidification on the solubility of calcium carbonate, since calcium hydroxide is one of the solutions.

This summative assessment addresses the essential question, How does calcium carbonate solubility in the ocean affect your daily life?

Students share their drawings on whiteboards and come to a consensus about the correct direction of heat flow. If students incorrectly identify the direction of heat flow, I show the salt dissolving simulation again and review the relative magnitudes of energies to break up the ionic lattice vs. solvation energy.

This summative assessment addresses the essential question, What economic impacts result from limits in equilibrium yields of industrial products?

Unit 8:

Acid-Base Equilibrium: Does It Produce or Absorb Protons?

Laboratory Investigations:

- Determination of the Acid Ionization Constant of a Weak Acid
- Determination of the Equilibrium Constant of an Indicator

Estimated Time:

4 weeks

Essential Questions:

- ▼ If our blood were not buffered, what activities and foods could be fatal to our bodies' functions?
- ▼ How can we determine how much more acidification our oceans can take?

Learning Objectives	Materials	Instructional Activities and Assessments
Generate or use a particulate representation of an acid (strong or weak or polyprotic) and a strong base to explain the species that will have large versus small concentrations at equilibrium. [LO 6.11, SP 1.1, SP 1.4, SP 2.3] Reason about the distinction between strong and weak acid solutions with similar values of pH, including the percent ionization of the acids, the concentrations needed to achieve the same pH, and the amount of base needed to reach the equivalence point in a titration. [LO 6.12, SP 1.4, SP 6.4, *connects to* 1.E.2]	**Web** "Acid-Base Solutions"	**Instructional Activity:** Students observe the PhET simulation and record their molecular observations of concentration of hydronium and hydroxide for a weak acid, strong acid, weak base, and strong base.
		Formative Assessment: Students determine the concentration of a weak acid needed to make the hydronium concentration the same as that in a 0.01 M solution of a strong acid.
Based on the dependence of K_w on temperature, reason that neutrality requires $[H^+] = [OH^-]$ as opposed to requiring pH = 7, including especially the applications to biological systems. [LO 6.14, SP 2.2, SP 6.2]	Stacy, Lesson 17: "Heartburn: Acids and Bases"	**Instructional Activity:** Students categorize several substances as strong acids, weak acids, strong bases, or weak bases based on pH and conductivity data. Students calculate $[H^+]$ and $[OH^-]$ for all solutions based upon K_w.
Identify a given solution as containing a mixture of strong acids and/or bases and calculate or estimate the pH (and concentrations of all chemical species) in the resulting solution. [LO 6.15, SP 2.2, SP 2.3, SP 6.4]		**Formative Assessment:** Students use conductivity, pH, and acid-base concentration data to determine and justify whether acids and bases are strong or weak.

As this is essentially an introductory activity, the determination can be done by trial and error. Later in the unit, when students have learned to do acid-base equilibrium calculations, the question can be revisited with calculations. If students can accomplish that, the instructional decision to move on is appropriate.

Students who do not correctly determine the concentration review the PhET simulation and then go over the calculation one-on-one with me.

This can be measured with universal indicator, pH paper, or a pH probe.

The solutions are discussed as a class, and a consensus is reached. If a correct consensus is not reached, I reteach the material and resurvey the class about the identities of the strong and weak solutions.

Essential Questions:

- ▼ If our blood were not buffered, what activities and foods could be fatal to our bodies' functions?
- ▼ How can we determine how much more acidification our oceans can take?

Learning Objectives	Materials	Instructional Activities and Assessments
Interpret titration data for monoprotic or polyprotic acids involving titration of a weak or strong acid by a strong base (or a weak or strong base by a strong acid) to determine the concentration of the titrant and the pK_a for a weak acid, or the pK_b for a weak base. [LO 6.13, SP 5.1, SP 6.4, *connects to* 1.E.2]	Hostage and Fossett, Experiment 10: "Determination of Acid Ionization Constant of a Weak Acid"	**Instructional Activity:** I divide the class into three groups, each of which titrates acetic acid with NaOH and determines K_a in one of three ways: the standard titration method, the half equivalence method, or the first derivative method.
		Formative Assessment: Students jigsaw their groups' calculations from the previous activity. The class determines the most accurate method, and comes up with a reason based on an error analysis. Students make posters with their calculations of K_a and are prepared to explain what is going on in each step of the calculation. Students with methods other than the one picked as most accurate are surveyed by me about their understanding of the other methods during a whole-class discussion.
		Summative Assessment: Students write formal lab reports in which they calculate K_a using their assigned method, but also address the theory and sources of error for the other two methods.
Design a buffer solution with a target pH and buffer capacity by selecting an appropriate conjugate acid-base pair and estimating the concentrations needed to achieve the desired capacity. [LO 6.18, SP 2.3, SP 4.2, SP 6.4]	Hostage and Fossett, Experiment 11: "Determination of Equilibrium Constant of an Indicator"	**Instructional Activity:** Students use a Vernier spectrophotometer to determine the K_a of bromcresol green indicator.
		Summative Assessment: Students write formal lab reports in which they detail their calculations for creating a buffered solution and use Beer's law to show the derivation of the indicator's equilibrium constant.

These methods are detailed extensively in the lab manual. The description is so thorough that the lab could precede any class instruction regarding acid-base equilibrium, provided students already have background knowledge of general equilibrium.

This summative assessment addresses the essential question, How can we determine how much more acidification our oceans can take?

A good follow-up question is, How would this experimental procedure need to be modified to find the K_a of phenolphthalein?

This summative assessment addresses the essential question, If our blood were not buffered, what activities and foods could be fatal to our bodies' functions?

Acid-Base Equilibrium: Does It Produce or Absorb Protons? *(continued)*

Essential Questions:

- ▼ If our blood were not buffered, what activities and foods could be fatal to our bodies' functions?
- ▼ How can we determine how much more acidification our oceans can take?

Learning Objectives	Materials	Instructional Activities and Assessments
Given an arbitrary mixture of weak and strong acids and bases (including polyprotic systems), determine which species will react strongly with one another (i.e., with $K > 1$) and what species will be present in large concentrations at equilibrium. [LO 6.17, SP 6.4] Relate the predominant form of a chemical species involving a labile proton (i.e., protonated/deprotonated form of a weak acid) to the pH of a solution and the pK_a associated with the labile proton. [LO 6.19, SP 2.3, SP 5.1, SP 6.4]		**Instructional Activity:** Students perform equilibrium calculations in which they write net ionic reactions for the addition of acids and salts, calculate equilibrium concentrations and equilibrium constants based upon initial conditions, calculate the pH and concentration of all species in the solution, and/or infer the relative strengths of the weak acids or bases from given equilibrium concentrations.
Identify a given solution as being the solution of a monoprotic weak acid or base (including salts in which one ion is a weak acid or base), calculate the pH and concentration of all species in the solution, and/or infer the relative strengths of the weak acids or bases from given equilibrium concentrations. [LO 6.16, SP 2.2, SP 6.4]		**Formative Assessment:** Students take a series of quizzes that progress in difficulty from fundamental (calculate pH at equilibrium based upon initial concentrations) to complex (determine mass of basic salt to make solution have set pH, weak acid titration). Students are presented with the option of self-differentiating by selecting the level of quiz they feel comfortable assessing themselves with.
Identify a solution as being a buffer solution and explain the buffer mechanism in terms of the reactions that would occur on addition of acid or base. [LO 6.20, SP 6.4]		**Instructional Activity:** Students observe a PEOE demonstration in which titration curves are produced by the titration of a strong and weak acid with 0.1 M NaOH. Students explain what is going on in the "buffering zone" of the curve by writing the reactions that occur between the strong base and weak acid present.
		Formative Assessment: Students take a quiz in which they calculate the pH at several points in the titration curve of a weak acid with a strong base. They also identify a solution as a buffer and describe what happens to that buffer with the addition of an acid or base.

For example, students who do extensive preparation outside of class can elect to take the challenging quiz first. If they pass, they can take on the role of tutor/mentor in class to help struggling classmates.

Students who do not pass a quiz attend an after-school review session, where I review the correct answers to that quiz. Students are then assigned supplemental online reading with practice problems to do (which I review) before retaking the quiz.

Students who do not pass attend an after-school review session in which I reteach how to interpret a weak acid/strong base titration curve. They then review their Cornell notes on this topic and are given another titration calculation.

Essential Questions:
- ▼ If our blood were not buffered, what activities and foods could be fatal to our bodies’ functions?
- ▼ How can we determine how much more acidification our oceans can take?

Learning Objectives	Materials	Instructional Activities and Assessments
		Summative Assessment: Students take a unit exam that covers acid-base equilibrium, buffer, and titration topics.

This summative assessment addresses the following essential questions:
- If our blood were not buffered, what activities and foods could be fatal to our bodies’ functions?
- How can we determine how much more acidification our oceans can take?

Resources

General Resources

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Hague, George R., and Jane D. Smith. *The Ultimate Chemical Equations Handbook*. Batavia, IL: Flinn Scientific, 2001.

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Supplementary Resources

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DeWane, Marilyn, and Cheri Smith, eds. *AP Chemistry: 2006–2007 Professional Development Workshop Materials: Special Focus: Chemical Equilibrium.* New York: The College Board, 2006. Accessed June 8, 2012. http://apcentral.collegeboard.com/apc/public/repository/Chemistry_SF_Equilibrium.pdf.

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Laidler, Keith J. and John H. Meiser. *Physical Chemistry*. 2nd ed. Boston, MA: Houghton Mifflin, 1995.

Luft, Julie, Randy L. Bell, and Julie Gess-Newsome. *Science as Inquiry in the Secondary Setting*. Arlington, VA: NSTA Press, 2008.

Unit 1 (Atoms, Reactions, and Stoichiometry: Connecting the Macroscopic World with the Nanoscopic) Resources

Cacciatore, Kristen, and Hannah Sevian. "Teaching Lab Report Writing through Inquiry: A Green Chemistry Stoichiometry Experiment for General Chemistry." *Journal of Chemistry Education* 83, no. 7 (July 2006): 1039–1041. http://pubs.acs.org/doi/abs/10.1021/ed083p1039.

Unit 2 (Reactions Involving Electron Transfer: Single Replacement, Redox, and Electrochemistry) Resources

"Metal/Metal Ion Reactions: A Laboratory Simulation." Chemical Education Research Group. Iowa State University. Accessed June 5, 2012. http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/Metal%3DMetalIonTutorialtgrt.pdf.

"Metals in Aqueous Solutions." Chemical Education Research Group. Iowa State University. Accessed June 5, 2012. http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/flashfiles/redox/home.html.

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Unit 3 (The Driving Forces: Chemical Energy and Thermodynamics) Resources

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Unit 4 (Atomic and Molecular Structure: Bonding in Covalent, Ionic, and Metallic Substances) Resources

"Bonding." Chemical Education Research Group. Iowa State University. Accessed June 14, 2012. http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/flashfiles/reaction/bonding1.html.

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“Models of the Hydrogen Atom.” PhET. University of Colorado at Boulder. Accessed June 7, 2012. http://PhET.colorado.edu/en/simulation/hydrogen-atom.

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Unit 5 (Particles and Interactions: Gases and Intermolecular Forces) Resources

“Salt Solution.” Chemical Education Research Group. Iowa State University. Accessed June 8, 2012. http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/flashfiles/thermochem/solutionSalt.html.

“State Variables and Ideal Gas Law.” Pearson Education. Accessed June 7, 2012. http://media.pearsoncmg.com/bc/aw_young_physics_11/pt1a/Media/Thermodynamics/StateVarIdealGasLaw/Main.html.

Unit 6 (Kinetics: How Fast Does It Go?) Resources

“The Kinetics of a Bleach Reaction.” Vernier. (Scroll down to Free Spectroscopy Labs.) Accessed June 8, 2012. http://www.vernier.com/products/sensors/spectrometers/svis-pl/.

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Unit 7 (General and Solubility Equilibrium: How Far Does It Go?) Resources

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Unit 8 (Acid-Base Equilibrium: Does It Produce or Absorb Protons?) Resources

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