AP CHEMISTRY

UNIT 7

Equilibrium

7–9%
AP EXAM WEIGHTING

~14–16
CLASS PERIODS

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

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

Personal Progress Check 7

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

- Short-answer
- Long-answer

UNIT 7

7–9% AP EXAM WEIGHTING

~14–16 CLASS PERIODS

Equilibrium

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

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

Developing Understanding

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

Building the Science Practices

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

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

Preparing for the AP Exam

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

UNIT AT A GLANCE

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

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UNIT AT A GLANCE *(cont'd)*

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

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

SAMPLE INSTRUCTIONAL ACTIVITIES

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

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

TOPIC 7.1
Introduction to Equilibrium

SUGGESTED SKILL

Argumentation

6.D

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

AVAILABLE RESOURCES

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

Required Course Content

ENDURING UNDERSTANDING

TRA-6

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

LEARNING OBJECTIVE

TRA-6.A

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

ESSENTIAL KNOWLEDGE

TRA-6.A.1

Many observable processes are reversible. Examples include evaporation and condensation of water, absorption and desorption of a gas, or dissolution and precipitation of a salt. Some important reversible chemical processes include the transfer of protons in acid-base reactions and the transfer of electrons in redox reactions.

TRA-6.A.2

When equilibrium is reached, no observable changes occur in the system. Reactants and products are simultaneously present, and the concentrations or partial pressures of all species remain constant.

TRA-6.A.3

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

TRA-6.A.4

Graphs of concentration, partial pressure, or rate of reaction versus time for simple chemical reactions can be used to understand the establishment of chemical equilibrium.

SUGGESTED SKILL

Model Analysis

4.D

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

TOPIC 7.2

Direction of Reversible Reactions

Required Course Content

ENDURING UNDERSTANDING

TRA-6

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

LEARNING OBJECTIVE

TRA-6.B

Explain the relationship between the direction in which a reversible reaction proceeds and the relative rates of the forward and reverse reactions.

ESSENTIAL KNOWLEDGE

TRA-6.B.1

If the rate of the forward reaction is greater than the reverse reaction, then there is a net conversion of reactants to products. If the rate of the reverse reaction is greater than that of the forward reaction, then there is a net conversion of products to reactants. An equilibrium state is reached when these rates are equal.

TOPIC 7.3

Reaction Quotient and Equilibrium Constant

SUGGESTED SKILL

Representing Data and Phenomena

3.A

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

AVAILABLE RESOURCES

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

Required Course Content

ENDURING UNDERSTANDING

TRA-7

A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.

LEARNING OBJECTIVE

TRA-7.A

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

ESSENTIAL KNOWLEDGE

TRA-7.A.1

The reaction quotient Q_c describes the relative concentrations of reaction species at any time. For gas phase reactions, the reaction quotient may instead be written in terms of pressures as Q_p. The reaction quotient tends toward the equilibrium constant such that at equilibrium $K_c = Q_c$ and $K_p = Q_p$. As examples, for the reaction

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

the equilibrium expression for (K_c, Q_c) is

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

and that for (K_p, Q_p) is

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

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

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

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LEARNING OBJECTIVE

TRA-7.A

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

ESSENTIAL KNOWLEDGE

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

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

TRA-7.A.2

The reaction quotient does not include substances whose concentrations (or partial pressures) are independent of the amount, such as for solids and pure liquids.

TOPIC 7.4

Calculating the Equilibrium Constant

SUGGESTED SKILL

Mathematical Routines

5.C

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

AVAILABLE RESOURCES

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

Required Course Content

ENDURING UNDERSTANDING

TRA-7

A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.

LEARNING OBJECTIVE

TRA-7.B

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

ESSENTIAL KNOWLEDGE

TRA-7.B.1

Equilibrium constants can be determined from experimental measurements of the concentrations or partial pressures of the reactants and products at equilibrium.

SUGGESTED SKILL

Argumentation

6.D

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

AVAILABLE RESOURCES

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

TOPIC 7.5

Magnitude of the Equilibrium Constant

Required Course Content

ENDURING UNDERSTANDING

TRA-7

A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.

LEARNING OBJECTIVE

TRA-7.C

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

ESSENTIAL KNOWLEDGE

TRA-7.C.1

Some equilibrium reactions have very large K values and proceed essentially to completion. Others have very small K values and barely proceed at all.

TOPIC 7.6

Properties of the Equilibrium Constant

Required Course Content

ENDURING UNDERSTANDING

TRA-7

A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.

LEARNING OBJECTIVE

TRA-7.D

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

ESSENTIAL KNOWLEDGE

TRA-7.D.1

When a reaction is reversed, K is inverted.

TRA-7.D.2

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

TRA-7.D.3

When reactions are added together, the K of the resulting overall reaction is the product of the K's for the reactions that were summed.

TRA-7.D.4

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

SUGGESTED SKILL

Mathematical Routines

5.A

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

AVAILABLE RESOURCES

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

SUGGESTED SKILL

Representing Data and Phenomena

3.A

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

AVAILABLE RESOURCES

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

TOPIC 7.7

Calculating Equilibrium Concentrations

Required Course Content

ENDURING UNDERSTANDING

TRA-7

A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.

LEARNING OBJECTIVE

TRA-7.E

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

ESSENTIAL KNOWLEDGE

TRA-7.E.1

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

TOPIC 7.8

Representations of Equilibrium

SUGGESTED SKILL

Representing Data and Phenomena

3.C

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

Required Course Content

ENDURING UNDERSTANDING

TRA-7

A system at equilibrium depends on the relationships between concentrations, partial pressures of chemical species, and equilibrium constant K.

LEARNING OBJECTIVE

TRA-7.F

Represent a system undergoing a reversible reaction with a particulate model.

ESSENTIAL KNOWLEDGE

TRA-7.F.1

Particulate representations can be used to describe the relative numbers of reactant and product particles present prior to and at equilibrium, and the value of the equilibrium constant.

SUGGESTED SKILL

Argumentation

6.F

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

AVAILABLE RESOURCES

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

TOPIC 7.9

Introduction to Le Châtelier's Principle

Required Course Content

ENDURING UNDERSTANDING

TRA-8

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

LEARNING OBJECTIVE

TRA-8.A

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

ESSENTIAL KNOWLEDGE

TRA-8.A.1

Le Châtelier's principle can be used to predict the response of a system to stresses such as addition or removal of a chemical species, change in temperature, change in volume/pressure of a gas-phase system, or dilution of a reaction system.

TRA-8.A.2

Le Châtelier's principle can be used to predict the effect that a stress will have on experimentally measurable properties such as pH, temperature, and color of a solution.

TOPIC 7.10

Reaction Quotient and Le Châtelier's Principle

Required Course Content

ENDURING UNDERSTANDING

TRA-8

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

LEARNING OBJECTIVE

TRA-8.B

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

ESSENTIAL KNOWLEDGE

TRA-8.B.1

A disturbance to a system at equilibrium causes Q to differ from K, thereby taking the system out of equilibrium. The system responds by bringing Q back into agreement with K, thereby establishing a new equilibrium state.

TRA-8.B.2

Some stresses, such as changes in concentration, cause a change in Q only. A change in temperature causes a change in K. In either case, the concentrations or partial pressures of species redistribute to bring Q and K back into equality.

SUGGESTED SKILL

Mathematical Routines

5.F

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

AVAILABLE RESOURCES

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

SUGGESTED SKILL

Mathematical Routines

5.B

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

TOPIC 7.11

Introduction to Solubility Equilibria

Required Course Content

ENDURING UNDERSTANDING

SPQ-5

The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.

LEARNING OBJECTIVE

SPQ-5.A

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

ESSENTIAL KNOWLEDGE

SPQ-5.A.1

The dissolution of a salt is a reversible process whose extent can be described by K_{sp}, the solubility-product constant.

SPQ-5.A.2

The solubility of a substance can be calculated from the K_{sp} for the dissolution process. This relationship can also be used to predict the relative solubility of different substances.

SPQ-5.A.3

The solubility rules (see TRA-2.A.5) can be quantitatively related to K_{sp}, in which K_{sp} values >1 correspond to soluble salts.

TOPIC 7.12
Common-Ion Effect

SUGGESTED SKILL
Question and Method

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

Required Course Content

ENDURING UNDERSTANDING

SPQ-5
The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.

LEARNING OBJECTIVE

SPQ-5.B
Identify the solubility of a salt, and/or the value of K_{sp} for the salt, based on the concentration of a common ion already present in solution.

ESSENTIAL KNOWLEDGE

SPQ-5.B.1
The solubility of a salt is reduced when it is dissolved into a solution that already contains one of the ions present in the salt. The impact of this "common-ion effect" on solubility can be understood qualitatively using Le Châtelier's principle or calculated from the K_{sp} for the dissolution process.

SUGGESTED SKILL

Question and Method

2.D

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

AVAILABLE RESOURCES

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

TOPIC 7.13
pH and Solubility

Required Course Content

ENDURING UNDERSTANDING

SPQ-5

The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.

LEARNING OBJECTIVE

SPQ-5.C

Identify the qualitative effect of changes in pH on the solubility of a salt.

ESSENTIAL KNOWLEDGE

SPQ-5.C.1

The solubility of a salt is pH sensitive when one of the constituent ions is a weak acid or base. These effects can be understood qualitatively using Le Châtelier's principle.

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

TOPIC 7.14

Free Energy of Dissolution

SUGGESTED SKILL

Model Analysis

4.D

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

AVAILABLE RESOURCES

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

Required Course Content

ENDURING UNDERSTANDING

SPQ-5

The dissolution of a salt is a reversible process that can be influenced by environmental factors such as pH or other dissolved ions.

LEARNING OBJECTIVE

SPQ-5.D

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

ESSENTIAL KNOWLEDGE

SPQ-5.D.1

The free energy change ($\Delta G°$) for dissolution of a substance reflects a number of factors: the breaking of the intermolecular interactions that hold the solid together, the reorganization of the solvent around the dissolved species, and the interaction of the dissolved species with the solvent. It is possible to estimate the sign and relative magnitude of the enthalpic and entropic contributions to each of these factors. However, making predictions for the total change in free energy of dissolution can be challenging due to the cancellations among the free energies associated with the three factors cited.