AP CHEMISTRY

UNIT 7

Equilibrium

7–9%
AP EXAM WEIGHTING

~13–15
CLASS PERIODS

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UNIT 7

7–9% AP EXAM WEIGHTING | **~13–15** CLASS PERIODS

Equilibrium

ESSENTIAL QUESTIONS

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

Developing Understanding

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

Building the Science Practices

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

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

Preparing for the AP Exam

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

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SUGGESTED SKILL

Argumentation

6.D

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

TOPIC 7.1
Introduction to Equilibrium

Required Course Content

LEARNING OBJECTIVE

7.1.A

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

ESSENTIAL KNOWLEDGE

7.1.A.1

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

7.1.A.2

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

7.1.A.3

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

7.1.A.4

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

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TOPIC 7.2
Direction of Reversible Reactions

SUGGESTED SKILL

Model Analysis

4.D

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

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.2.A Explain the relationship between the direction in which a reversible reaction proceeds and the relative rates of the forward and reverse reactions.	**7.2.A.1** If the rate of the forward reaction is greater than the reverse reaction, then there is a net conversion of reactants to products. If the rate of the reverse reaction is greater than that of the forward reaction, then there is a net conversion of products to reactants. An equilibrium state is reached when these rates are equal.

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SUGGESTED SKILL

Representing Data and Phenomena

3.A

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

AVAILABLE RESOURCES

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

TOPIC 7.3
Reaction Quotient and Equilibrium Constant

Required Course Content

LEARNING OBJECTIVE

7.3.A

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

ESSENTIAL KNOWLEDGE

7.3.A.1

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

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

the law of mass action indicates that the equilibrium expression for (K_c, Q_c) is

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

and that for (K_p, Q_p) is

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

Exclusion Statement: *Conversion between K_c and K_p will not be assessed on the AP Exam. Students should be aware of the conceptual differences and pay attention to whether K_c or K_p is used in an exam question.*

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LEARNING OBJECTIVE

7.3.A

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

ESSENTIAL KNOWLEDGE

Exclusion Statement: *Equilibrium calculations on systems where a dissolved species is in equilibrium with that species in the gas phase will not be assessed on the AP Exam.*

7.3.A.2

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

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SUGGESTED SKILL

Mathematical Routines

5.C

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

AVAILABLE RESOURCES

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

TOPIC 7.4
Calculating the Equilibrium Constant

Required Course Content

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

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TOPIC 7.5
Magnitude of the Equilibrium Constant

SUGGESTED SKILL

Argumentation

6.D

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

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.5.A Explain the relationship between very large or very small values of K and the relative concentrations of chemical species at equilibrium.	7.5.A.1 Some equilibrium reactions have very large K values and proceed essentially to completion. Others have very small K values and barely proceed at all.

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SUGGESTED SKILL

Mathematical Routines

5.A

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

TOPIC 7.6
Properties of the Equilibrium Constant

Required Course Content

LEARNING OBJECTIVE

7.6.A

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

ESSENTIAL KNOWLEDGE

7.6.A.1

When a reaction is reversed, K is inverted.

7.6.A.2

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

7.6.A.3

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

7.6.A.4

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

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TOPIC 7.7
Calculating Equilibrium Concentrations

Required Course Content

LEARNING OBJECTIVE

7.7.A

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

ESSENTIAL KNOWLEDGE

7.7.A.1

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

7.7.A.2

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

SUGGESTED SKILL

Representing Data and Phenomena

3.A

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

AVAILABLE RESOURCES

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

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SUGGESTED SKILL

Representing Data and Phenomena

3.C

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

TOPIC 7.8
Representations of Equilibrium

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.8.A Represent a system undergoing a reversible reaction with a particulate model.	**7.8.A.1** Particulate representations can be used to describe the relative numbers of reactant and product particles present prior to and at equilibrium, and the value of the equilibrium constant.

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TOPIC 7.9
Introduction to Le Châtelier's Principle

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.9.A Identify the response of a system at equilibrium to an external stress, using Le Châtelier's principle.	**7.9.A.1** Le Châtelier's principle can be used to predict the response of a system to stresses such as addition or removal of a chemical species, change in temperature, change in volume/pressure of a gas-phase system, or dilution of a reaction system.
	7.9.A.2 Le Châtelier's principle can be used to predict the effect that a stress will have on experimentally measurable properties such as pH, temperature, and color of a solution.

SUGGESTED SKILL

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**

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SUGGESTED SKILL

Mathematical Routines

5.F

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

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 13: Can We Make the Colors of the Rainbow? An Application of Le Châtelier's Principle**
- The Exam > **2022 Chief Reader Report**

TOPIC 7.10

Reaction Quotient and Le Châtelier's Principle

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
7.10.A Explain the relationships between Q, K, and the direction in which a reversible reaction will proceed to reach equilibrium.	**7.10.A.1** A disturbance to a system at equilibrium causes Q to differ from K, thereby taking the system out of equilibrium. The system responds by bringing Q back into agreement with K, thereby establishing a new equilibrium state.
	7.10.A.2 Some stresses, such as changes in concentration, cause a change in Q only. A change in temperature causes a change in K. In either case, the concentrations or partial pressures of species redistribute to bring Q and K back into equality.

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TOPIC 7.11
Introduction to Solubility Equilibria

SUGGESTED SKILL

Mathematical Routines

5.B

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

Required Course Content

LEARNING OBJECTIVE

7.11.A

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

ESSENTIAL KNOWLEDGE

7.11.A.1

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

7.11.A.2

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

7.11.A.3

The solubility rules (see 4.7.A.5) can be quantitatively related to K_{sp}, in which K_{sp} values >1 correspond to soluble salts.

7.11.A.4

The molar solubility of one or more species in a saturated solution can be used to calculate the K_{sp} of a substance.

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SUGGESTED SKILL

Question and Method

2.F

Explain how modifications to an experimental procedure will alter results.

TOPIC 7.12
Common-Ion Effect

Required Course Content

LEARNING OBJECTIVE

7.12.A

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

ESSENTIAL KNOWLEDGE

7.12.A.1

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

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