AP CHEMISTRY

UNIT 8

Acids and Bases

11–15%
AP EXAM WEIGHTING

~14–16
CLASS PERIODS

UNIT 8

11–15% AP EXAM WEIGHTING | **~14–16** CLASS PERIODS

Acids and Bases

ESSENTIAL QUESTIONS

- How is pH related to the concentration and strength of an acid, a base, or a mixture of them?
- How does acid or base strength relate to the concentrations of reactants and products when a system reaches equilibrium?
- Why are some acids stronger than others?
- How does your body maintain pH balance?

Developing Understanding

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

Building the Science Practices

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

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

Preparing for the AP Exam

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

SUGGESTED SKILL

Mathematical Routines

5.B

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

AVAILABLE RESOURCES

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

TOPIC 8.1

Introduction to Acids and Bases

Required Course Content

LEARNING OBJECTIVE

8.1.A

Calculate the values of pH and pOH, based on K_w and the concentration of all species present in a neutral solution of water.

ESSENTIAL KNOWLEDGE

8.1.A.1

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

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

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

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

8.1.A.2

Water autoionizes with an equilibrium constant K_w.

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

8.1.A.3

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

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

8.1.A.4

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

TOPIC 8.2

pH and pOH of Strong Acids and Bases

SUGGESTED SKILL

Mathematical Routines

5.B

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

Required Course Content

LEARNING OBJECTIVE

8.2.A

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

ESSENTIAL KNOWLEDGE

8.2.A.1

Molecules of a strong acid (e.g., HCl, HBr, HI, $HClO_4$, H_2SO_4, and HNO_3) will completely ionize in aqueous solution to produce hydronium ions and the conjugate base of the acid. As such, the concentration of H_3O^+ in a strong acid solution is equal to the initial concentration of the strong acid, and thus the pH of the strong acid solution is easily calculated.

8.2.A.2

When dissolved in solution, strong bases (e.g., group I and II hydroxides) completely dissociate to produce hydroxide ions. As such, the concentration of OH^- in a strong base solution is equal to the initial concentration of a group I hydroxide and double the initial concentration of a group II hydroxide, and thus the pOH (and pH) of the strong base solution is easily calculated.

SUGGESTED SKILL

Mathematical Routines

5.C

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

TOPIC 8.3
Weak Acid and Base Equilibria

Required Course Content

LEARNING OBJECTIVE

8.3.A

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

ESSENTIAL KNOWLEDGE

8.3.A.1

Weak acids react with water to produce hydronium ions. However, only a small percentage of molecules of a weak acid will ionize in this way. Thus, the concentration of H_3O^+ is much less than the initial concentration of the molecular acid, and the vast majority of the acid molecules remain un-ionized.

8.3.A.2

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

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

EQN: $pK_a = -\log K_a$

8.3.A.3

Weak bases react with water to produce hydroxide ions in solution. However, ordinarily just a small percentage of the molecules of a weak base in solution will ionize in this way. Thus, the concentration of OH^- in the solution does not equal the initial concentration of the base, and the vast majority of the base molecules remain un-ionized.

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LEARNING OBJECTIVE

8.3.A

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

ESSENTIAL KNOWLEDGE

8.3.A.4

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

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

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

8.3.A.5

The percent ionization of a weak acid (or base) can be calculated from its $\mathrm{p}K_a$ ($\mathrm{p}K_b$) and the initial concentration of the acid (base). The percent ionization can also be calculated from the initial concentration of the acid (base) and the equilibrium concentration of any of the species in the equilibrium expression.

8.3.A.6

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

EQN: $K_w = K_a \times K_b$

EQN: $\mathrm{p}K_w = \mathrm{p}K_a + \mathrm{p}K_b$

SUGGESTED SKILL

Mathematical Routines

5.F

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

AVAILABLE RESOURCES

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

TOPIC 8.4
Acid-Base Reactions and Buffers

Required Course Content

LEARNING OBJECTIVE

8.4.A

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

ESSENTIAL KNOWLEDGE

8.4.A.1

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

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(l).$$

The pH of the resulting solution may be determined from the concentration of excess reagent.

8.4.A.2

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

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

If the weak acid is in excess, then a buffer solution is formed, and the pH can be determined from the Henderson-Hasselbalch (H–H) equation (see 8.9.A.1). If the strong base is in excess, then the pH can be determined from the moles of excess hydroxide ion and the total volume of solution. If they are equimolar, then the (slightly basic) pH can be determined from the equilibrium represented by the equation:

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

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LEARNING OBJECTIVE

8.4.A

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

ESSENTIAL KNOWLEDGE

8.4.A.3

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

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

If the weak base is in excess, then a buffer solution is formed, and the pH can be determined from the $\mathrm{H{-}H}$ equation. If the strong acid is in excess, then the pH can be determined from the moles of excess hydronium ion and the total volume of solution. If they are equimolar, then the (slightly acidic) pH can be determined from the equilibrium represented by the equation:

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

8.4.A.4

When a weak acid and a weak base are mixed, they will react to an equilibrium state whose reaction may be represented by the equation:

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

SUGGESTED SKILL

Mathematical Routines

5.D

Identify information presented graphically to solve a problem.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 14: How Do the Structure and the Initial Concentration of an Acid and a Base Influence the pH of the Resultant Solution During a Titration?**
- The Exam > **2022 Chief Reader Report**

TOPIC 8.5
Acid-Base Titrations

Required Course Content

LEARNING OBJECTIVE

8.5.A

Explain results from the titration of a mono- or polyprotic acid or base solution, in relation to the properties of the solution and its components.

ESSENTIAL KNOWLEDGE

8.5.A.1

An acid-base reaction can be carried out under controlled conditions in a titration. A titration curve, plotting pH against the volume of titrant added, is useful for summarizing results from a titration.

8.5.A.2

At the equivalence point for titrations of monoprotic acids or bases, the number of moles of titrant added is equal to the number of moles of analyte originally present. This relationship can be used to obtain the concentration of the analyte. This is the case for titrations of strong acids/bases and weak acids/bases.

8.5.A.3

For titrations of weak acids/bases, it is useful to consider the point halfway to the equivalence point, that is, the half-equivalence point. At this point, there are equal concentrations of each species in the conjugate acid-base pair, for example, for a weak acid $[\mathrm{HA}] = [\mathrm{A}^-]$. Because $\mathrm{pH} = \mathrm{p}K_a$ when the conjugate acid and base have equal concentrations, the $\mathrm{p}K_a$ can be determined from the pH at the half-equivalence point in a titration.

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LEARNING OBJECTIVE

8.5.A

Explain results from the titration of a mono- or polyprotic acid or base solution, in relation to the properties of the solution and its components.

ESSENTIAL KNOWLEDGE

8.5.A.4

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

8.5.A.5

For polyprotic acids, titration curves can be used to determine the number of acidic protons. In doing so, the major species present at any point along the curve can be identified, along with the $\mathrm{p}K_a$ associated with each proton in a weak polyprotic acid.

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

SUGGESTED SKILL

Argumentation

6.C

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

TOPIC 8.6
Molecular Structure of Acids and Bases

Required Course Content

LEARNING OBJECTIVE

8.6.A

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

ESSENTIAL KNOWLEDGE

8.6.A.1

The protons on a molecule that will participate in acid-base reactions, and the relative strength of these protons, can be inferred from the molecular structure.

i. Strong acids (such as HCl, HBr, HI, $HClO_4$, H_2SO_4, and HNO_3) have very weak conjugate bases that are stabilized by electronegativity, inductive effects, resonance, or some combination thereof.

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

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

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

v. Electronegative elements tend to stabilize the conjugate base relative to the conjugate acid, and so increase acid strength.

TOPIC 8.7

pH and pK_a

Required Course Content

LEARNING OBJECTIVE

8.7.A

Explain the relationship between the predominant form of a weak acid or base in solution at a given pH and the pK_a of the conjugate acid or the pK_b of the conjugate base.

ESSENTIAL KNOWLEDGE

8.7.A.1

The protonation state of an acid or base (i.e., the relative concentrations of HA and A^-) can be predicted by comparing the pH of a solution to the pK_a of the acid in that solution. When solution $pH < \text{acid } pK_a$, the acid form has a higher concentration than the base form. When solution $pH > \text{acid } pK_a$, the base form has a higher concentration than the acid form.

8.7.A.2

Acid-base indicators are substances that exhibit different properties (such as color) in their protonated versus deprotonated state, making that property respond to the pH of a solution.

8.7.A.3

To ensure accurate results in a titration experiment, acid-base indicators should be selected that have a pK_a close to the pH at the equivalence point.

SUGGESTED SKILL

Question and Method

2.D

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

AVAILABLE RESOURCES

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

SUGGESTED SKILL

Argumentation

6.D

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

AVAILABLE RESOURCES

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

TOPIC 8.8
Properties of Buffers

Required Course Content

LEARNING OBJECTIVE

8.8.A

Explain the relationship between the ability of a buffer to stabilize pH and the reactions that occur when an acid or a base is added to a buffered solution.

ESSENTIAL KNOWLEDGE

8.8.A.1

A buffer solution contains a large concentration of both members in a conjugate acid-base pair. The conjugate acid reacts with added base and the conjugate base reacts with added acid. These reactions are responsible for the ability of a buffer to stabilize pH.

TOPIC 8.9

Henderson-Hasselbalch Equation

Required Course Content

LEARNING OBJECTIVE

8.9.A

Identify the pH of a buffer solution based on the identity and concentrations of the conjugate acid-base pair used to create the buffer.

ESSENTIAL KNOWLEDGE

8.9.A.1

The pH of the buffer is related to the pK_a of the acid and the concentration ratio of the conjugate acid-base pair. This relation is a consequence of the equilibrium expression associated with the dissociation of a weak acid, and is described by the Henderson-Hasselbalch equation. Adding small amounts of acid or base to a buffered solution does not significantly change the ratio of $[A^-]/[HA]$ and thus does not significantly change the solution pH. The change in pH on addition of acid or base to a buffered solution is therefore much less than it would have been in the absence of the buffer.

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

Exclusion Statement: *Computation of the change in pH resulting from the addition of an acid or a base to a buffer will not be assessed on the AP Exam.*

Exclusion Statement: *Derivation of the Henderson-Hasselbalch equation will not be assessed on the AP Exam.*

SUGGESTED SKILL

Mathematical Routines

5.F

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

AVAILABLE RESOURCES

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

SUGGESTED SKILL

Argumentation

6.G

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

AVAILABLE RESOURCES

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

TOPIC 8.10

Buffer Capacity

Required Course Content

LEARNING OBJECTIVE

8.10.A

Explain the relationship between the buffer capacity of a solution and the relative concentrations of the conjugate acid and conjugate base components of the solution.

ESSENTIAL KNOWLEDGE

8.10.A.1

Increasing the concentration of the buffer components (while keeping the ratio of these concentrations constant) keeps the pH of the buffer the same but increases the capacity of the buffer to neutralize added acid or base.

8.10.A.2

When a buffer has more conjugate acid than base, it has a greater buffer capacity for addition of added base than acid. When a buffer has more conjugate base than acid, it has a greater buffer capacity for addition of added acid than base.

TOPIC 8.11
pH and Solubility

Required Course Content

LEARNING OBJECTIVE

8.11.A

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

ESSENTIAL KNOWLEDGE

8.11.A.1

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

Exclusion Statement: *Computations of solubility as a function of pH will not be assessed on the AP Exam.*

SUGGESTED SKILL

Question and Method

2.D

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

AVAILABLE RESOURCES

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