**AP CHEMISTRY** 

# **UNIT 8** Acids and Bases



# AP

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 8**

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

Long-answer

# ↔ Developing Understanding

UNIT

8

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. The dissolution of a solid in a solvent can also be understood by applying the principles of chemical equilibrium quickly. 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

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 acidstrong base and a weak acid-strong base 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 struggle 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 struggle with unit conversion, or they can confuse half-equivalence, equivalence, and endpoint. Or, they may struggle to understand what general types of titration curves represent. Teachers can provide students with multiple opportunities to describe why titration curves have characteristic shapes for certain acidbase 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. Practicing using the half-titration point helps to visualize and clarify ratios between acid/conjugate base.

### **BIG IDEA 2**

#### Structure and Properties SAP

- How are reactions involving acids and bases related to pH?
- How does your body maintain pH balance?



# **UNIT AT A GLANCE**

uring erstandinç		Class Periods	
End	Торіс	Suggested Skill	~14-15 CLASS PERIODS
SAP-9	8.1 Introduction to Acids and Bases	<b>5.B</b> Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	<b>8.2</b> pH and pOH of Strong Acids and Bases	<b>5.B</b> Identify an appropriate theory, definition, or mathematical relationship to solve a problem.	
	<b>8.3</b> Weak Acid and Base Equilibria	<b>5.C</b> Explain the relationship between variables within an equation when one variable changes.	
	8.4 Acid-Base Reactions and Buffers	<b>5.F</b> 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).	
	<b>8.5</b> Acid-Base Titrations	<b>5.D</b> Identify information presented graphically to solve a problem.	
	8.6 Molecular Structure of Acids and Bases	<b>6.C</b> Support a claim with evidence from representations or models at the particulate level, such as the structure of atoms and/or molecules.	
SAP-10	<b>8.7</b> pH and pK <sub>a</sub>	2.D Make observations or collect data from representations of laboratory setups or results, while attending to precision where appropriate.	
	8.8 Properties of Buffers	<b>6.D</b> Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	
	<b>8.9</b> Henderson-Hasselbalch Equation	<b>5.F</b> Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	
	8.10 Buffer Capacity	<b>6.G</b> Explain how potential sources of experimental error may affect the experimental results.	
	Go to AP Classroom to assign th	e Personal Progress Check for Unit 8	

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	8.2 8.3	<b>Post-Lab Discussion</b> Rainbow Acid Indicator (Flinn Scientific Item U0012) is added to 0.001 M solutions of HCl, $H_2SO_4$ , and $HC_2H_3O_2$ . Have students reason out why the pH values are not the same, and introduce the concept of $K_a$ . Then have them calculate the pH of each solution to explain their earlier observations. Percent ionization is discussed and how ICE charts reflect the percent ionization is explained.	
2	8.5	<b>Post-Lab Discussion</b> After collecting data on a weak acid/strong base titration, have students create a titration curve (pH as a function of the volume of base added). Then have them identify relative points on the graph based on group discussion (e.g., equivalence point).	
3	8.8	<b>Demo with Q&amp;A</b> Add an Alka-Seltzer tablet to 200 mL of water and pour the resulting solution into three small beakers. Add deionized water to three more beakers. Add universal indicator to all six beakers and then add strong acids and strong bases to each beaker to demonstrate buffering ability and buffer capacity. Have students develop particulate-level drawings to illustrate what is happening in the beakers in the context of "buffering ability."	
4	8.9 8.10	<b>Simulations</b> Using a ChemCollective virtual lab, ask students to develop a buffer that will have a particular pH after an amount of strong acid is added.	



UNIT

2

X Mathematical Routines

5.B Identif

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



AVAILABLE RESOURCESThe Exam >

2017 Chief Reader Report

# TOPIC 8.1 Introduction to Acids and Bases

# **Required Course Content**

#### **ENDURING UNDERSTANDING**

#### SAP-9

The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

#### **LEARNING OBJECTIVE**

#### SAP-9.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**

#### SAP-9.A.1

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

EQN:  $pH = -log[H_3O^+]$ 

EQN:  $pOH = -log[OH^-]$ 

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.

#### SAP-9.A.2

Water autoionizes with an equilibrium constant  $K_{w}$ .

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

#### SAP-9.A.3

In pure water, pH = pOH is called a neutral solution. At 25°C,  $pK_w = 14.0$  and thus pH = pOH = 7.0.

EQN:  $pK_w = 14 = pH + pOH$  at 25°C

#### SAP-9.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

### **Required Course Content**

#### **ENDURING UNDERSTANDING**

#### SAP-9

The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

#### **LEARNING OBJECTIVE**

#### SAP-9.B

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

#### **ESSENTIAL KNOWLEDGE**

#### SAP-9.B.1

Molecules of a strong acid (e.g., HCl, HBr, HI, HClO<sub>4</sub>, H<sub>2</sub>SO<sub>4</sub>, and HNO<sub>3</sub>) will completely ionize in aqueous solution to produce hydronium ions. 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.

#### SAP-9.B.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 the strong base, and thus the pOH (and pH) of the strong base solution is easily calculated.



X Mathematical Routines

UNIT

8



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

#### AVAILABLE RESOURCES

 Classroom Resource > Quantitative Skills in the AP Sciences



UNIT

8

X 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**

#### **ENDURING UNDERSTANDING**

#### SAP-9

The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

#### **LEARNING OBJECTIVE**

#### SAP-9.C

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

#### **ESSENTIAL KNOWLEDGE**

#### SAP-9.C.1

Weak acids react with water to produce hydronium ions. However, molecules of a weak acid will only partially ionize in this way. In other words, only a small percentage of the molecules of a weak acid are ionized in a solution. 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.

#### SAP-9.C.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:  $pK_a = -\log K_a$ 

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#### **LEARNING OBJECTIVE**

#### SAP-9.C

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

#### **ESSENTIAL KNOWLEDGE**

#### SAP-9.C.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.

#### SAP-9.C.4

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

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

EQN:  $pK_b = -\log K_b$ 

#### SAP-9.C.5

The percent ionization of a weak acid (or base) can be calculated from its  $pK_a$  ( $pK_b$ ) and the initial concentration of the acid (base).

#### SUGGESTED SKILL

UNIT

8

X Mathematical Routines

#### 5.F

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

# TOPIC 8.4 Acid-Base Reactions and Buffers

# **Required Course Content**

#### **ENDURING UNDERSTANDING**

#### SAP-9

The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

#### **LEARNING OBJECTIVE**

#### SAP-9.D

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

#### **ESSENTIAL KNOWLEDGE**

#### SAP-9.D.1

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

 $\mathrm{H}^{+}(aq) + \mathrm{OH}^{-}(aq) \rightarrow \mathrm{H}_{2}\mathrm{O}(l).$ 

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

#### SAP-9.D.2

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

 $HA(aq) + OH^{-}(aq) \rightleftharpoons A^{-}(aq) H_{2}O(l).$ 

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 SAP-10.C.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:

 $A^{-}(aq) + H_2O(l) \rightleftharpoons HA(aq) + OH^{-}(aq).$ 

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#### **LEARNING OBJECTIVE**

#### SAP-9.D

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

#### **ESSENTIAL KNOWLEDGE**

#### SAP-9.D.3

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

 $B(aq) + H_3O^+(aq) \rightleftharpoons HB^+(aq) + H_2O(l).$ 

If the weak base is in excess, then a buffer solution is formed, and the pH can be determined from the 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:

 $HB^+(aq) + H_2O(l) \rightleftharpoons B(aq) + H_3O^+(aq).$ 

#### SAP-9.D.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:

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



UNIT

8

X 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?

# TOPIC 8.5 Acid-Base Titrations

# **Required Course Content**

#### **ENDURING UNDERSTANDING**

#### SAP-9

The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

#### **LEARNING OBJECTIVE**

#### SAP-9.E

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**

#### SAP-9.E.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.

#### SAP-9.E.2

At the equivalence point, 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.

#### SAP-9.E.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 [HA] = [A<sup>-</sup>]. Because  $pH = pK_a$  when the conjugate acid and base have equal concentrations, the  $pK_a$  can be determined from the pH at the half-equivalence point in a titration.

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#### **LEARNING OBJECTIVE**

#### SAP-9.E

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**

#### SAP-9.E.4

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  $pK_a$  associated with each proton in a weak polyprotic acid.

#### COMPUTATION OF THE CONCENTRATION OF EACH SPECIES PRESENT IN THE TITRATION CURVE FOR POLYPROTIC ACIDS WILL NOT BE ASSESSED ON THE AP EXAM.

**Rationale:** Such computations for titration of monoprotic acids are within the scope of the course, as is qualitative reasoning regarding what species are present in large versus small concentrations at any point in titration of a polyprotic acid. However, additional computations of the concentration of each species present in the titration curve for polyprotic acids may encourage algorithmic calculations rather than deepen understanding.

🕅 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.

UNIT

8

# TOPIC 8.6 Molecular Structure of Acids and Bases

# **Required Course Content**

#### **ENDURING UNDERSTANDING**

#### SAP-9

The chemistry of acids and bases involves reversible proton-transfer reactions, with equilibrium concentrations being related to the strength of the acids and bases involved.

#### **LEARNING OBJECTIVE**

#### SAP-9.F

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

#### **ESSENTIAL KNOWLEDGE**

#### SAP-9.F.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.

- a. Strong acids (such as HCl, HBr, HI, HClO<sub>4</sub>, H<sub>2</sub>SO<sub>4</sub>, and HNO<sub>3</sub>) have very weak conjugate bases that are stabilized by electronegativity, inductive effects, resonance, or some combination thereof.
- b. Carboxylic acids are one common class of weak acid.
- c. Strong bases (such as group I and II hydroxides) have very weak conjugate acids.
- d. Common weak bases include nitrogenous bases such as ammonia as well as carboxylate ions.
- e. Electronegative elements tend to stabilize the conjugate base relative to the conjugate acid, and so increase acid strength.

# TOPIC 8.7 pH and pK<sub>a</sub>

### **Required Course Content**

#### **ENDURING UNDERSTANDING**

#### SAP-10

A buffered solution resists changes to its  $pH \mbox{ when small}$  amounts of acid or base are added.

#### **LEARNING OBJECTIVE**

#### SAP-10.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**

#### SAP-10.A.1

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

#### SAP-10.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.

#### SUGGESTED SKILL

Question and Method

UNIT

8

#### 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



#### SUGGESTED SKILL



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**

#### **ENDURING UNDERSTANDING**

SAP-10

A buffered solution resists changes to its pH when small amounts of acid or base are added.

#### **LEARNING OBJECTIVE**

#### SAP-10.B

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**

#### SAP-10.B.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**

#### **ENDURING UNDERSTANDING**

SAP-10

A buffered solution resists changes to its  $pH \mbox{ when small amounts of acid or base} \ are added.$ 

#### **LEARNING OBJECTIVE**

#### SAP-10.C

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**

#### SAP-10.C.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 of acid or base to a buffered solution of 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: 
$$pH = pK_a + log \frac{[A^-]}{[HA]}$$

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.

DERIVATION OF THE HENDERSON-HASSELBALCH EQUATION WILL NOT BE ASSESSED ON THE AP EXAM.

#### SUGGESTED SKILL

X Mathematical Routines

UNIT

8

#### 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?



UNIT

8

ጰ 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**

#### **ENDURING UNDERSTANDING**

#### SAP-10

A buffered solution resists changes to its pH when small amounts of acid or base are added.

#### **LEARNING OBJECTIVE**

#### SAP-10.D

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**

#### SAP-10.D.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.

#### SAP-10.D.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.