19.4

1 FOCUS

Objectives

19.4.1 Define the products of an acid-base reaction.

19.4.2 Explain how acid-base titration is used to calculate the concentration of an acid or a base.

19.4.3 Explain the concept of equivalence in neutralization reactions.

19.4.4 Describe the relationship between equivalence point and the end point of a titration.

Guide for Reading

Build Vocabulary L2

Graphic Organizers Have students write definitions of *standard solution, titration,* and *end point* in the first column of a two column table. Have them describe how these three terms are related in the second column.

Reading Strategy L2

Relate Text and Visuals Have students reference the visuals as they learn about titration.

2 INSTRUCT

Connecting to Your World

Have students study the photograph and read the text that opens the section. Ask, **What is a neutralization reaction?** *(the reaction between an acid and a base, producing a salt and water)*

Why not use a stronger base to provide quicker relief from excess stomach acid? *(The stronger base would be too corrosive for the digestive tract.)*

Acid-Base Reactions

Discuss L2

Ask students if they have witnessed or read a news report about people trying to clean up a chemical spill on a highway or at a factory. Ask, **If a spill involves an acid, what type of treatment is possible?** *(A weak base in powder form, such as sodium carbonate, can be spread over the spill to absorb, react with, and neutralize the acid.)*

19.4 Neutralization Reactions

Guide for Reading

Key Concepts

- What are the products of the reaction of an acid with a base?
- What is the endpoint of a titration?

Vocabulary

neutralization reactions
equivalence point
standard solution
titration
end point

Reading Strategy

Identifying a Sequence A sequence is the order in which a series of events occurs. As you read about acid-base titrations, list the steps that should be used in carrying out a precise titration. Include the reactants and how they are measured, the indicator, and what to look for as the titration nears its end point.

Connecting to Your World Nearly all of the adult population suffers from acid indigestion at some time. Although hydrochloric acid is always present in the stomach, an excess can cause heartburn and a feeling of nausea. A common way to relieve the pain of acid indigestion is to take antacids to neutralize the stomach acid. The active ingredient in many antacids is sodium hydrogen carbonate, aluminum hydroxide, or magnesium hydroxide. In this section, you will learn what a neutralization reaction is.

Acid-Base Reactions

If you mix a solution of a strong acid containing hydronium (hydrogen) ions with a solution of a strong base that has an equal number of hydroxide ions, a neutral solution results. The final solution has properties that are characteristic of neither an acidic nor a basic solution. Consider these examples:

$$HCl(aq) + NaOH(aq) \longrightarrow NaCl(aq) + H_2O(l)$$

$$H_2SO_4(aq) + 2KOH(aq) \longrightarrow K_2SO_4(aq) + 2H_2O(l)$$

In each example, a strong acid reacts with a strong base. If solutions of these substances are mixed in the mole ratios specified by the balanced equation, neutral solutions will result. Similar reactions of weak acids and/or weak bases do not usually produce neutral solutions. In general, however, reactions in which an acid and a base react in an aqueous solution to produce a salt and water are called **neutralization reactions.** The formation of water in a neutralization reaction is shown in Figure 19.20.

Neutralization reactions are one way to prepare pure samples of salts. You could prepare potassium chloride, for example, by mixing equal molar quantities of hydrochloric acid and potassium hydroxide. An aqueous solution of potassium chloride would result. You could heat the solution to evaporate the water, leaving the salt potassium chloride. Table 19.9 lists some common salts and their applications.

In general, the reaction of an acid with a base produces water and one of a class of compounds called salts. When you hear the word *salt,* you may think of the substance that flavors your French fries or scrambled eggs. Table salt (sodium chloride) is one example of a salt, but there are many more. Salts are compounds consisting of an anion from an acid and a cation from a base.

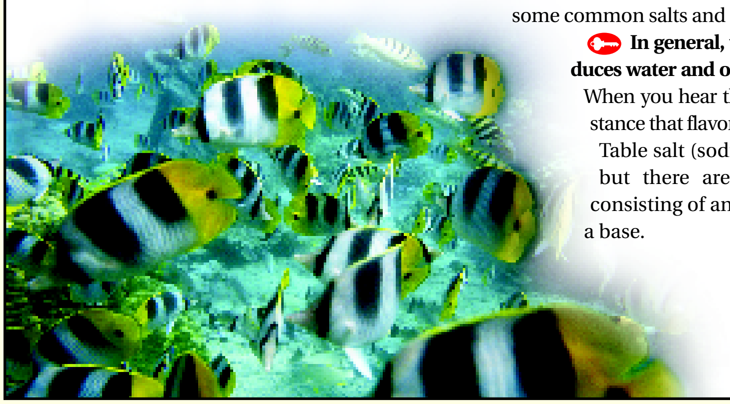


Figure 19.19 For fish and other aquatic animals to survive, the water in which they live must be maintained at the proper pH.

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 19.4
- **Core Teaching Resources,** Section 19.4 Review
- **Transparencies,** T225–T226
- **Laboratory Manual,** Labs 41, 42, 43
- **Small-Scale Chemistry Laboratory Manual,** Lab 31
- **Probeware Lab Manual,** The Neutralizing Power of Antacids, Small-Scale Titrations

Technology

- **Interactive Textbook with ChemASAP,** Problem-Solving 19.30, 19.33, Simulation 26, Assessment 19.4

Table 19.9

Some Salts and Their Applications

Name	Formula	Applications
Ammonium sulfate	$(NH_4)_2SO_4$	Fertilizer
Barium sulfate	$BaSO_4$	Gastrointestinal studies; white pigment
Calcium chloride	$CaCl_2$	De-icing roadways and sidewalks
Potassium chloride	KCl	Sodium-free salt substitute
Silver bromide	AgBr	Photographic emulsions
Sodium hydrogen carbonate (baking soda)	$NaHCO_3$	Antacid
Sodium carbonate decahydrate (washing soda)	$Na_2CO_3 \cdot 10H_2O$	Glass manufacture; water softener
Sodium chloride (table salt)	NaCl	Body electrolyte; chlorine manufacture

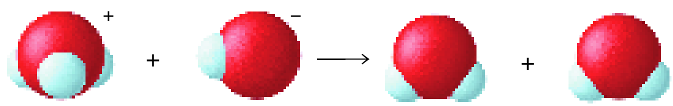


Figure 19.20 In a neutralization reaction, hydronium ions (H_3O^+) combine with hydroxide ions (OH^-) to form neutral water.

The properties of acids, bases, and salts help explain many diverse phenomena. The usefulness of antacids, for example, depends on the process of acid-base neutralization. Farmers use a similar process to control the pH of soil.

Titration

Acids and bases sometimes, but not always, react in a 1:1 mole ratio.

$$\underset{1\text{ mol}}{HCl(aq)} + \underset{1\text{ mol}}{NaOH(aq)} \longrightarrow \underset{1\text{ mol}}{NaCl(aq)} + \underset{1\text{ mol}}{H_2O(l)}$$

When sulfuric acid reacts with sodium hydroxide, however, the ratio is 1:2. Two moles of the base sodium hydroxide are required to neutralize one mole of H_2SO_4.

$$\underset{1\text{ mol}}{H_2SO_4(aq)} + \underset{2\text{ mol}}{2NaOH(aq)} \longrightarrow \underset{1\text{ mol}}{Na_2SO_4(aq)} + \underset{2\text{ mol}}{2H_2O(l)}$$

Similarly, hydrochloric acid and calcium hydroxide react in a 2:1 ratio.

$$\underset{2\text{ mol}}{2HCl(aq)} + \underset{1\text{ mol}}{Ca(OH)_2(aq)} \longrightarrow \underset{1\text{ mol}}{CaCl_2(aq)} + \underset{2\text{ mol}}{2H_2O(l)}$$

You will notice in the preceding examples that the number of moles of hydrogen ions provided by the acid are equivalent to the number of hydroxide ions provided by the base. When an acid and base are mixed, the **equivalence point** is when the number of moles of hydrogen ions equals the number of moles of hydroxide ions.

Checkpoint ***What is the equivalence point of a reaction between an acid and a base?***

Titration

Discuss L2

Point out that neutralization is a process that occurs whenever an acid reacts with a base in the mole ratios specified by the balanced equation. Explain that not all neutralization reactions produce neutral solutions. The relative strengths of the reactants determines whether the solution will be acidic, basic, or neutral.

TEACHER Demo

Titration Using Indicators L2

Purpose Students observe properties of titration.

Materials equimolar solutions of HCl and NaOH, phenolphthalein, electric stirrer with a magnetic stir bar, beaker, table salt

Safety Wear protective goggles and laboratory apron.

Procedure Write the following equation on the board: $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$

Prepare equimolar solutions of HCl and NaOH. Add a few drops of phenolphthalein indicator to the NaOH solution. Slowly add the HCl to the NaOH while carefully stirring. If possible, use an electric stirrer with a magnetic stir bar. Ask, **What happens to the color of the solution as the acid is added?** *(The deep pink color slowly fades until the solution becomes colorless.)* Remind students that phenolphthalein is an acid-base indicator that is colorless at pH lower than 8. Have a few volunteers come up and gently touch the outside of the reaction beaker. Ask them to describe their observations to the class.

Ask, **Is the neutralization reaction endothermic or exothermic?** *(exothermic)*

Display a quantity of table salt equivalent to the amount of salt that could be retrieved if the neutral solution were evaporated.

Answers to...

Checkpoint the point at which mol H^+ = mol OH^-

Sample Problem 19.6

Answers

30. $H_3PO_4 + 3KOH \rightarrow K_3PO_4 + 3H_2O$; 1.56 mol $H_3PO_4 \times 3$ mol KOH/1 mol $H_3PO_4 = 4.68$ mol KOH

31. $HNO_3 + NaOH \rightarrow NaNO_3 + H_2O$; 0.20 mol $HNO_3 \times 1$ mol NaOH/1 mol $HNO_3 = 0.20$ mol NaOH

Practice Problems Plus L2

How many moles of aluminum hydroxide are needed to neutralize 2.30 mol of sulfuric acid? *(1.53 moles)*

Math Handbook

For a math refresher and practice, direct students to dimensional analysis, page R66.

Use Visuals L1

Table 19.5 and Figure 19.21 Have students study Table 19.5 and Figure 19.21. Red cabbage, when used as an acid-base indicator, turns red between pH 2 and 3, pink between pH 3 and 4, and green between pH 8-12. Ask, **What color will emerge when testing household ammonia?** *(green)* **Lemon juice?** *(red)* **Seawater?** *(green)*

SAMPLE PROBLEM 19.6

Finding the Number of Moles of an Acid in Neutralization

How many moles of sulfuric acid are required to neutralize 0.50 mol of sodium hydroxide?

1 Analyze ***List the knowns and the unknown.***

Knowns

- mol NaOH = 0.50 mol
- $H_2SO_4(aq) + 2NaOH(aq) \longrightarrow Na_2SO_4(aq) + 2H_2O(l)$
- $\dfrac{\text{mol } H_2SO_4}{\text{mol NaOH}} = \dfrac{1}{2}$

Unknown

- moles H_2SO_4 = ? mol

2 Calculate ***Solve for the unknown.***

The mole ratio of H_2SO_4 to NaOH is 1:2. The necessary number of moles of H_2SO_4 is calculated using this ratio.

$$0.50 \text{ mol NaOH} \times \frac{1 \text{ mol } H_2SO_4}{2 \text{ mol NaOH}} = 0.25 \text{ mol } H_2SO_4$$

3 Evaluate ***Does the result make sense?***

Because the mole ratio of H_2SO_4 to NaOH is 1:2, the expected number of moles of H_2SO_4 should be half the given number of moles of NaOH. The answer should have two significant figures.

Practice Problems

30. How many moles of potassium hydroxide are needed to completely neutralize 1.56 mol of phosphoric acid?

31. How many moles of sodium hydroxide are required to neutralize 0.20 mol of nitric acid?

Math Handbook

For help with dimensional analysis, go to page R66.

Interactive Textbook

Problem-Solving 19.30 Solve Problem 30 with the help of an interactive guided tutorial.

with ChemASAP

You can determine the concentration of acid (or base) in a solution by performing a neutralization reaction. You must use an appropriate acid-base indicator to show when neutralization has occurred. As you can see in Figure 19.21, the juice of the red cabbage is an acid-base indicator. In the laboratory, phenolphthalein is often the preferred indicator for acid-base neutralization reactions. Solutions that contain phenolphthalein turn from colorless to deep pink as the pH of the solution changes from acidic to basic. In slightly basic solutions, the indicator is very faintly pink.

Figure 19.21 Red cabbage juice is used as an acid-base indicator. As the solution changes from highly acidic to basic, the color changes from red to violet to green to yellow. **Predicting** ***Would the yellow solution have a high or low pH?***

614 Chapter 19

Facts and Figures

Acids, Bases, and Curly Hair

Curly hair from a permanent wave involves an acid-base neutralization reaction. The waving solution is basic and has a pH of about 9.20. The active ingredient in the waving solution is often an ammonium compound that is applied once the hair has been rolled. After a specified time, the hair is rinsed to remove the excess base. Then a neutralizer is applied. The neutralizer is an acid solution that has a pH range of 2 to 6. If the hair is exposed to the waving solution for too long a period of time, the hair's texture and appearance are damaged.

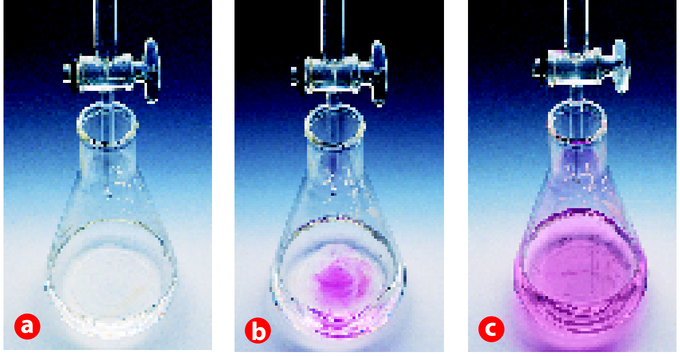


Figure 19.22 The titration of an acid with a base is shown here. (a) A known volume of an acid (plus a few drops of phenolphthalein indicator) in a flask is placed beneath a buret filled with a base of known concentration. (b) Base is slowly added from the buret to the acid while the flask is gently swirled. (c) A change in the color of the indicator signals that neutralization has occurred.

The steps in a neutralization reaction are as follows.

1. A measured volume of an acid solution of unknown concentration is added to a flask.
2. Several drops of the indicator are added to the solution while the flask is gently swirled.
3. Measured volumes of a base of known concentration are mixed into the acid until the indicator just barely changes color.

The process of adding a known amount of solution of known concentration to determine the concentration of another solution is called **titration.** The solution of known concentration is called the **standard solution.** Use a buret to add the standard solution. A titration is continued until the indicator shows that neutralization has just occurred. The point at which the indicator changes color is the **end point** of the titration. The titration of an acid of unknown concentration with a standard base is shown in Figure 19.22. You can use a similar procedure to find the concentration of a base using a standard acid.

Figure 19.23 shows how the pH of a solution changes during the titration of a strong acid (HCl) with a strong base (NaOH). The pH of the initial acid solution is low. As the base is added, the pH increases because some of the acid is neutralized. As the titration approaches the point of neutralization, at a pH of 7, the pH increases dramatically as hydrogen ions are used up. Once past the point of neutralization, additional base produces a further increase of pH. **The point of neutralization is the end point of the titration.** At this point, the contents of the beaker consist of only H_2O and NaCl, which is the salt derived from the strong acid HCl and the strong base NaOH, plus a trace of indicator.

Interactive Textbook

Simulation 26 Simulate the titration of several acids and bases and observe patterns in the pH at equivalence.

with ChemASAP

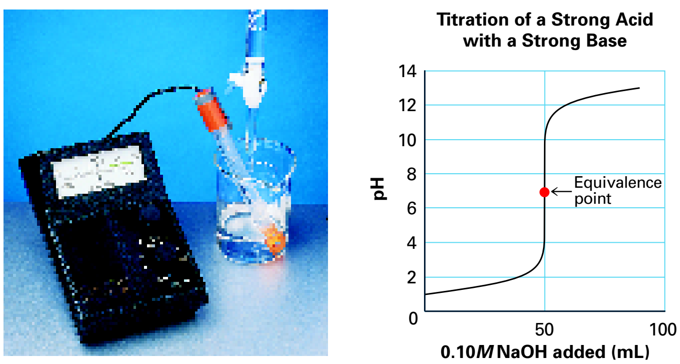


Figure 19.23 In this titration of a strong acid with a strong base, 0.10*M* NaOH is slowly added from a buret to 50.0 mL of 0.10*M* HCl in the beaker. The equivalence point, the midpoint on the vertical portion of the pH titration curve, occurs at 50.0 mL of NaOH added. **Interpreting Diagrams** ***What is true concerning [H$^+$] and [OH$^-$] at the equivalence point?***

TEACHER Demo

Titration Using a pH Meter L2

Purpose Students observe properties of the equivalence point.

Materials equimolar solutions of HCl and NaOH, phenolphthalein, beaker, buret, pH meter, graph paper

Procedure Repeat the demo described on page 613. This time place the base in a beaker and the acid in a buret. Use a pH meter to monitor the titration. Construct a graph similar to the one in Figure 19.23

Expected Outcome Compared with Figure 19.23, the graph will be reversed because an acidic solution is being added to a basic solution.

Ask, **What happens to the graph as the titration nears its equivalence point?** *(The slope becomes very steep.)* **What would happen to the pH if a small amount of base were added to the beaker after the equivalence point is reached?** *(The pH would increase dramatically.)*

Add some base to the beaker and observe the pH. Ask, **What can be done to regain the equivalence point?** *(Add acid from the buret.)*

Answers to...

Figure 19.21 high

Figure 19.23 They are equal for this titration.

Sample Problem 19.7

Answers

32. 25.0 mL KOH × 1.00 mol KOH/1000mL KOH × 1 mol HCl/1 mol KOH × 1000 mL HCl/0.45 mol HCl = 56 mL HCl

33. 38.5 mL NaOH × 0.150 mol NaOH/1000 mL NaOH × 1 mol H_3PO_4/3 mol NaOH = 0.00193 mol H_3PO_4; 0.001923 mol H_3PO_4/0.0150 L H_3PO_4 = 0.129*M* H_3PO_4

Practice Problems Plus L2

What is the molarity of sulfuric acid if 25.0 mL of the solution is neutralized by 25.5 mL of 0.50M KOH? *(0.26M)*

Math Handbook

For a math refresher and practice, direct students to dimensional analysis, page R66.

3 ASSESS

Evaluate Understanding L2

Ask students to summarize the titration process in their own words. *(During a titration, equivalent volumes of an acid and of a base are determined. One is a standard solution with a known concentration; the concentration of the other solution is not known.)*

Reteach L1

Have students use Figures 19.22 and 19.23 to describe how titration works.

Connecting Concepts

Acid-base neutralizations are double displacement reactions. The positive ions are exchanged between the acid and base reactants; the products are a salt and water.

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 19.4.

with ChemASAP

SAMPLE PROBLEM 19.7

Determining the Concentration of an Acid by Titration

A 25-mL solution of H_2SO_4 is completely neutralized by 18 mL of 1.0*M* NaOH. What is the concentration of the H_2SO_4 solution?

1 Analyze *List the knowns and the unknown.*

Knowns

- molarity base = 1.0*M* NaOH
- volume base = 18 mL = 0.018 L
- volume acid = 25 mL = 0.025 L
- $H_2SO_4(aq) + 2NaOH(aq) \longrightarrow Na_2SO_4(aq) + 2H_2O(l)$

Unknown

- molarity acid = ?*M* H_2SO_4

Use the molarity to convert the volume of base to moles of base. Use the mole ratio to find the number of moles of H_2SO_4. Calculate the molarity by dividing the number of moles of H_2SO_4 by the number of liters of H_2SO_4.

The conversion steps are as follows:

$$\text{L NaOH} \longrightarrow \text{mol NaOH} \longrightarrow \text{mol } H_2SO_4 \longrightarrow M\ H_2SO_4$$

2 Calculate *Solve for the unknown.*

$$0.018\ \text{L NaOH} \times \frac{1.0\ \text{mol NaOH}}{1\ \text{L NaOH}} \times \frac{1\ \text{mol } H_2SO_4}{2\ \text{mol NaOH}} = 0.0090\ \text{mol } H_2SO_4$$

$$\text{molarity} = \frac{\text{moles}}{\text{liters}} = \frac{0.0090\ \text{mol}}{0.025\ \text{L}} = 0.36\ M$$

The $[H_2SO_4]$ is 0.36*M*.

3 Evaluate *Does the result make sense?*

Because the volume of acid was greater than the volume of base, the concentration is less than 1.0*M*. The answer has two significant figures.

Math Handbook

For help with dimensional analysis, go to page R66.

Practice Problems

32. How many milliliters of 0.45*M* HCl will neutralize 25.0 mL of 1.00*M* KOH?

33. What is the molarity of H_3PO_4 if 15.0 mL is completely neutralized by 38.5 mL of 0.150*M* NaOH?

Interactive Textbook

Problem-Solving 19.33 Solve Problem 33 with the help of an interactive guided tutorial.

with ChemASAP

19.4 Section Assessment

34. **Key Concept** What are the products of a reaction between an acid and a base?

35. **Key Concept** What occurs at the endpoint of a titration?

36. How many moles of HCl are required to neutralize aqueous solutions of these bases?
  a. 2 mol NH_3 **b.** 0.1 mol $Ca(OH)_2$

37. Write complete balanced equations for the following acid-base reactions?
  a. $H_2SO_4(aq) + KOH(aq) \longrightarrow$
  b. $H_3PO_4(aq) + Ca(OH)_2(aq) \longrightarrow$
  c. $HNO_3(aq) + Mg(OH)_2(aq) \longrightarrow$

Connecting Concepts

Types of Reactions Reread the information on types of chemical reactions in Section 11.2. Which type of reaction are all acid-base neutralizations? Explain your answer.

Interactive Textbook

Assessment 19.4 Test yourself on the concepts in Section 19.4.

with ChemASAP

Section 19.4 Assessment

34. a salt and water
35. neutralization
36. a. 2 mol **b.** 0.2 mol
37. a. $H_2SO_4 + 2KOH \rightarrow 2H_2O + K_2SO_4$
b. $2H_3PO_4 + 3Ca(OH)_2 \rightarrow 6H_2O + Ca_3(PO_4)_2$
c. $2HNO_3 + Mg(OH)_2 \rightarrow 2H_2O + Mg(NO_3)_2$

Small-Scale LAB

Ionization Constants of Weak Acids

Purpose

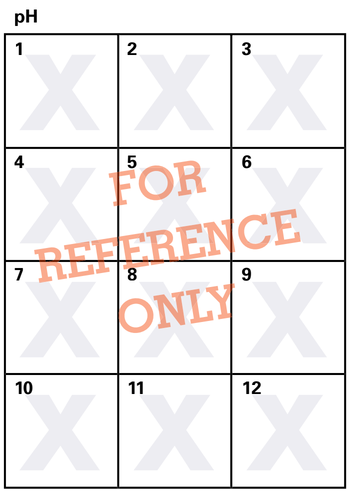
To measure ionization constants of weak acids such as bromocresol green (BCG).

Materials

- ruler
- reaction surface
- pH buffer and BCG

Procedure

1. On separate sheets of paper, draw two grids similar to the one below. Make each square 2 cm on each side.
2. Place a reaction surface over one of the grids and place one drop of BCG in each square.
3. Place one drop of pH buffer in each square corresponding to its pH value.
4. Use the second grid as a data table to record your observations for each solution.



Analyze

Using your experimental data, record the answers to the following questions below your data table.

1. What is the color of the lowest-pH solutions?
2. What is the color of the highest-pH solutions?
3. At which pH does the bromcresol green change from one color to the other? At which pH does an intermediate color exist?

An acid-base indicator is usually a weak acid with a characteristic color. Because bromcresol green is an acid, it is convenient to represent its rather complex formula as HBCG. HBCG ionizes in water according to the following equation.

$$\underset{\text{(yellow)}}{HBCG} + H_2O = \underset{\text{(blue)}}{BCG^-} + H_3O^+$$

The K_a expression is

$$K_a = \frac{[BCG^-] \times [H_3O^+]}{[HBCG]}$$

When $[BCG^-] = [HBCG]$, $K_a = [H_3O^+]$.

4. What color is the conjugate acid of BCG^-?
5. What color is the conjugate base of HBCG?
6. What color is an equal mixture of the conjugate acid and conjugate base of bromcresol green? At what pH does this equal mixture occur?

You're The Chemist

The following small-scale activities allow you to develop your own procedures and analyze the results.

1. **Design It!** Design and carry out an experiment to measure the K_a of several more acid-base indicators. Record the colors of the conjugate acids (low pH) and the conjugate bases (high pH). Determine the K_a for each acid.
2. **Analyze It!** Explain in your own words how to measure the K_a of a colored acid-base indicator. Explain what you would do and how you would interpret your results.

Small-Scale LAB

Ionization Constants of Weak Acids L2

Objective After completing this activity, students will be able to: measure ionization constants of weak acids

Prep Time 1 hour

Advance Prep

Solution	Preparation
*0.04% BTB	100 mg in 16.0 mL 0.01*M* NaOH, dilute to 250 mL
*0.04% BCG	100 mg in 14.3 mL 0.01*M* NaOH, dilute to 250 mL
*0.04% BPB	100 mg in 14.9 mL 0.01*M* NaOH, dilute to 250 mL
*0.04% MCP	100 mg in 26.2 mL 0.01*M* NaOH, dilute to 250 mL
*0.04% TB	100 mg in 21.5 mL 0.01*M* NaOH, dilute to 250 mL
0.1% phenolphthalein	250 mg in 250 mL of 70% 2-propanol
0.05% MO	125 mg in 250 mL
0.02% AYR	50 mg in 250 mL

*Can dissolve sodium salt directly in 250 mL of distilled water.

Obtain commercially-prepared pH buffers or prepare pH buffer solutions according to instructions in a reference such as the Handbook of Chemistry and Physics.

Class Time 30 minutes

Safety Make sure that students wear aprons, goggles, and disposable gloves throughout the lab.

Expected Outcome Students measure the pH at which common indicators change colors and use their data to calculate the ionization constants of weak acids.

Analyze

1. pH solutions 1 to 3 are yellow.
2. pH solutions 5 to 12 are blue.
3. pH solution 4 is green (an intermediate between yellow and blue).
4. The conjugate acid, HBCG, is yellow.
5. The conjugate base, BCG^-, is blue.
6. The equal mixture of HBCG and BCG^- is green at pH = 4.

You're the Chemist

1. Results will vary depending on the indicators chosen.
2. To measure the K_a of a colored acid-base indicator, mix one drop of the indicator solution with one drop of each pH 1–12 buffer solution. Look for the pH of the color change. This pH is close to the K_a of the acid.