The reaction of sulfur oxides with water explains how sulfurous and sulfuric acids are formed in the atmosphere. Sulfuric acid is a strong acid, like hydrochloric acid, so it reacts with metal window frames and ornaments, breaking down the metal and producing hydrogen gas. Similarly, acid precipitation reacts with limestone or marble structures, including statues, to release carbon dioxide gas. In both cases, the solids deteriorate during the chemical reactions that occur.

Evaluation

(t) Student answers may vary. Sources of error include the loss of the gas produced during some of the reactions, the quantities used, the purity of the samples, and the time for the reaction. A suggestion for improvements may include increasing the quantities of reactants.

Synthesis

(u) If an acidic solution, such as lemon juice or a soft drink, were allowed to remain on the metal shelves in a refrigerator, the metal would likely corrode or become oxidized. This effect could lead to the deterioration of the metal shelves.

(v) You should never use an oven cleaner on aluminum pots and pans because oven cleaner contains a base, such as sodium hydroxide, which reacts with aluminum to form hydrogen gas. The pots and pans would become damaged by this reaction, and there is a potential explosion from the large amounts of hydrogen gas produced.

(w) Some buildings, marble statues, and metal bridges are composed of limestone, $CaCO_3$, and metals. All of these substances react with acidic solutions. Therefore, acidic precipitation can cause the deterioration of these structures.

4.11 REACTIONS OF ACIDS AND BASES

PRACTICE

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Understanding Concepts

1. (a) A characteristic chemical reaction of a known reactant yields specific products. For example, all acids react with active metals to produce hydrogen gas. You can gain clues about an unknown substance by seeing how it participates in a reaction and by observing the formation of specific products.

   (b) Acid–metal reaction: acid + active metal $\rightarrow$ salt + $H_{2(g)}$
   $2\ HCl_{(aq)} + Cu_{(s)} \rightarrow CuCl_{2(aq)} + H_{2(g)}$
   Acid–carnbonate reaction: acid + carbonate $\rightarrow$ salt + $CO_{2(g)} + H_2O_{(l)}$
   $2\ HCl_{(aq)} + MgCO_{3(s)} \rightarrow MgCl_{2(aq)} + CO_{2(g)} + H_2O_{(l)}$
   Acid–base reaction: acid + base $\rightarrow$ salt + $H_2O_{(l)}$
   $2\ HCl_{(aq)} + Ba(OH)_{2(aq)} \rightarrow BaCl_{2(aq)} + 2\ H_2O_{(l)}$

2. (a) Balanced chemical equations for the neutralization of hydrochloric acid:
   $6\ HCl_{(aq)} + 2\ Al_{(s)} \rightarrow 2\ AlCl_{3(aq)} + 3\ H_{2(g)}$
   $HCl_{(aq)} + NaOH_{(aq)} \rightarrow NaCl_{(aq)} + H_2O_{(l)}$
   $2\ HCl_{(aq)} + Na_2CO_{3(s)} \rightarrow 2\ NaCl_{(aq)} + CO_{2(g)} + H_2O_{(l)}$

   (b) The advantage of neutralizing hydrochloric acid with aluminum is that one mole of aluminum, $Al_{(s)}$, neutralizes three times as much hydrochloric acid, $HCl_{(aq)}$. One disadvantage of neutralizing hydrochloric acid with aluminum is that potentially explosive hydrogen gas is produced.

   The advantage of neutralizing hydrochloric acid with sodium hydroxide, $NaOH_{(aq)}$, is that harmless sodium chloride, $NaCl_{(aq)}$, and water are produced. The disadvantage of neutralization with a strong base is that the reaction may release dangerous amounts of heat.

   The advantage of neutralizing hydrochloric acid with sodium carbonate, $Na_2CO_{3(s)}$, is that one mole of sodium carbonate neutralizes two times as much hydrochloric acid. The disadvantage of neutralizing hydrochloric acid with sodium carbonate is that carbon dioxide gas is released, which may cause a glass container to explode.

3. (a) $KOH_{(aq)} + HCl_{(aq)} \rightarrow KCl_{(aq)} + H_2O_{(l)}$
   (b) $LiOH_{(aq)} + HNO_{3(aq)} \rightarrow LiNO_{3(aq)} + H_2O_{(l)}$
   (c) $2\ KOH_{(aq)} + H_2SO_{4(aq)} \rightarrow K_2SO_{4(aq)} + 2\ H_2O_{(l)}$

TRY THIS ACTIVITY: A NEUTRALIZATION REACTION

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3. The pH of the solution is 7.
   (a) $NaOH_{(aq)} + HCl_{(aq)} \rightarrow NaCl_{(aq)} + H_2O_{(l)}$
   (b) If the neutralized solution were evaporated to dryness, you would expect to see a solid white material in the bottom of the container. Although it is not recommended, you could taste the material to confirm that it is sodium chloride (table salt). You could also dissolve the material in water and measure the conductivity of the solution. This method would determine if the crystals were composed of an ionic compound. To specifically identify the ions, you could perform a detailed analysis, such as systematic qualitative analysis.

PRACTICE

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Understanding Concepts

4. $H_2SO_{3(aq)} + 2\ NaOH_{(aq)} \rightarrow Na_2SO_{3(aq)} + 2\ H_2O_{(l)}$

$$v_{H_2SO_3} = 25.0 \text{ mL} = 0.0250 \text{ L}$$
$$v_{NaOH} = 10.72 \text{ mL} = 0.01072 \text{ L}$$
$$c_{NaOH} = 0.105 \text{ mol/L}$$

$$\begin{aligned} n_{NaOH} &= v_{NaOH}c_{NaOH} \\ &= 0.01072 \text{ L} \times 0.105 \text{ mol/L} \\ n_{NaOH} &= 0.001126 \text{ mol} \end{aligned}$$

$$\begin{aligned} n_{H_2SO_3} &= 0.001126 \text{ mol NaOH} \times \frac{1 \text{ mol } H_2SO_3}{2 \text{ mol NaOH}} \\ &= 0.000563 \text{ mol} \end{aligned}$$

$$\begin{aligned} c_{H_2SO_3} &= \frac{n_{H_2SO_3}}{v_{H_2SO_3}} \\ &= \frac{0.000563 \text{ mol}}{0.0250 \text{ L}} \\ c_{H_2SO_3} &= 0.0225 \text{ mol/L} \end{aligned}$$

The concentration of sulfurous acid in the water sample is 0.0225 mol/L.

5. $HBr_{(aq)} + LiOH_{(aq)} \rightarrow LiBr_{(aq)} + H_2O_{(l)}$

$$v_{HBr} = 25.0 \text{ mL} = 0.0250 \text{ L}$$
$$v_{LiOH} = 57.50 \text{ mL} = 0.05750 \text{ L}$$
$$c_{LiOH} = 0.200 \text{ mol/L}$$

$$\begin{aligned} n_{LiOH} &= v_{LiOH}c_{LiOH} \\ &= 0.05750 \text{ L} \times 0.200 \text{ mol/L} \\ n_{LiOH} &= 0.0115 \text{ mol} \end{aligned}$$

$$\begin{aligned} n_{HBr} &= 0.0115 \text{ mol LiOH} \times \frac{1 \text{ mol HBr}}{1 \text{ mol LiOH}} \\ &= 0.0115 \text{ mol} \end{aligned}$$

$$c_{HBr} = \frac{n_{HBr}}{v_{HBr}}$$
$$= \frac{0.0115 \text{ mol}}{0.0250 \text{ L}}$$
$$c_{HBr} = 0.460 \text{ mol/L}$$

The concentration of hydrobromic acid is 0.460 mol/L.

6. $HCl_{(aq)} + NaOH_{(aq)} \rightarrow NaCl_{(aq)} + H_2O_{(l)}$

$$v_{HCl} = 30.0 \text{ mL} = 0.0300 \text{ L}$$
$$v_{NaOH} = 86.19 \text{ mL} = 0.08619 \text{ L}$$
$$c_{NaOH} = 0.765 \text{ mol/L}$$

$$n_{NaOH} = v_{NaOH}c_{NaOH}$$
$$= 0.08619 \text{ L} \times 0.765 \text{ mol/L}$$
$$n_{NaOH} = 0.0659 \text{ mol}$$

$$n_{HCl} = 0.0659 \text{ mol NaOH} \times \frac{1 \text{ mol HCl}}{1 \text{ mol NaOH}}$$
$$= 0.0659 \text{ mol}$$

$$c_{HCl} = \frac{n_{HCl}}{v_{HCl}}$$
$$= \frac{0.0659 \text{ mol}}{0.0300 \text{ L}}$$
$$c_{HCl} = 2.20 \text{ mol/L}$$

The concentration of hydrochloric acid is 2.20 mol/L.

7. $H_2SO_{4(aq)} + 2\ KOH_{(aq)} \rightarrow K_2SO_{4(aq)} + 2\ H_2O_{(l)}$

$$v_{H_2SO_4} = 10.0 \text{ mL} = 0.0100 \text{ L}$$
$$v_{KOH} = 9.44 \text{ mL} = 0.00944 \text{ L}$$
$$c_{KOH} = 0.050 \text{ mol/L}$$

$$n_{KOH} = v_{KOH}c_{KOH}$$
$$= 0.00944 \text{ L} \times 0.050 \text{ mol/L}$$
$$n_{KOH} = 0.000472 \text{ mol}$$

$$n_{H_2SO_4} = 0.000472 \text{ mol KOH} \times \frac{1 \text{ mol } H_2SO_4}{2 \text{ mol KOH}}$$
$$= 0.000236 \text{ mol}$$

$$c_{H_2SO_4} = \frac{n_{H_2SO_4}}{v_{H_2SO_4}}$$
$$= \frac{0.000236 \text{ mol}}{0.0100 \text{ L}}$$
$$c_{H_2SO_4} = 0.0236 \text{ mol/L}$$

The concentration of sulfuric acid in the water is 0.024 mol/L.

8. $2\ HCl_{(aq)} + Ba(OH)_{2(aq)} \rightarrow BaCl_{2(aq)} + 2\ H_2O_{(l)}$

$$v_{HCl} = 10.0\text{ mL} = 0.0100\text{ L}$$
$$v_{Ba(OH)_2} = 150.01\text{ mL} = 0.15001\text{ L}$$
$$c_{Ba(OH)_2} = 0.0974\text{ mol/L}$$

$$n_{Ba(OH)_2} = v_{Ba(OH)_2} c_{Ba(OH)_2}$$
$$= 0.15001\text{ L} \times 0.0974\text{ mol/L}$$
$$n_{Ba(OH)_2} = 0.0146\text{ mol}$$

$$n_{HCl} = 0.0146\text{ mol Ba(OH)}_2 \times \frac{2\text{ mol HCl}}{1\text{ mol Ba(OH)}_2}$$
$$= 0.0292\text{ mol}$$

$$c_{HCl} = \frac{n_{HCl}}{v_{HCl}}$$
$$= \frac{0.0292\text{ mol}}{0.0100\text{ L}}$$
$$c_{HCl} = 2.92\text{ mol/L}$$

The concentration of hydrochloric acid in the scale remover is 2.92 mol/L.

SECTION 4.11 QUESTIONS

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Understanding Concepts

1. The three characteristic reactions of acids are a single displacement reaction with an active metal to produce a salt and hydrogen gas; a double displacement reaction with a carbonate to produce a salt, carbon dioxide gas, and water; and a double displacement neutralization reaction with a base to produce a salt and water.
2. (a) $KOH_{(aq)} + HCl_{(aq)} \rightarrow KCl_{(aq)} + H_2O_{(l)}$
   (b) $LiOH_{(aq)} + HBr_{(aq)} \rightarrow LiBr_{(aq)} + H_2O_{(l)}$
   (c) $NaOH_{(aq)} + HNO_{3(aq)} \rightarrow NaNO_{3(aq)} + H_2O_{(l)}$
   (d) $Ca(OH)_{2(aq)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(aq)} + 2\ H_2O_{(l)}$
   (e) $Ba(OH)_{2(aq)} + 2\ HCl_{(aq)} \rightarrow BaCl_{2(aq)} + 2\ H_2O_{(l)}$
   (f) $Mg(OH)_{2(aq)} + 2\ HC_2H_3O_{2(aq)} \rightarrow Mg(C_2H_3O_2)_{2(aq)} + 2\ H_2O_{(l)}$
3. Several trials are done in a titration to improve the accuracy and reliability of the result. At least three trials should be performed, and the average of the three most consistent titrant volumes are used for further calculations.
4. The data given in **Figure 4** are listed in **Table 1**.

Table 1 Titration of $H_2SO_{4(aq)}$ with $NaOH_{(aq)}$

Trial	1	2	3	4	Average
Final burette reading	12.10 mL	23.65 mL	35.10 mL	46.55 mL	
Initial burette reading	0.35 mL	12.10 mL	23.65 mL	35.10 mL	
Volume of NaOH added	11.75 mL	11.55 mL	11.45 mL	11.45 mL	11.48 mL*

* Average of Trials 2, 3, and 4

$H_2SO_{4(aq)} + 2\ NaOH_{(aq)} \rightarrow Na_2SO_{4(aq)} + 2\ H_2O_{(l)}$

$v_{H_2SO_4} = 10.00\text{ mL} = 0.01000\text{ L}$

$v_{NaOH} = 11.48\text{ mL} = 0.01148\text{ L}$

$c_{NaOH} = 0.484\text{ mol/L}$

$$\begin{aligned} n_{NaOH} &= v_{NaOH}c_{NaOH} \\ &= 0.01148\text{ L} \times 0.484\text{ mol/L} \\ n_{NaOH} &= 0.005556\text{ mol} \end{aligned}$$

$$\begin{aligned} n_{H_2SO_4} &= 0.005556\text{ mol NaOH} \times \frac{1\text{ mol }H_2SO_4}{2\text{ mol NaOH}} \\ &= 0.002778\text{ mol} \end{aligned}$$

$$\begin{aligned} c_{H_2SO_4} &= \frac{n_{H_2SO_4}}{v_{H_2SO_4}} \\ &= \frac{0.002778\text{ mol}}{0.0100\text{ L}} \\ c_{H_2SO_4} &= 0.2778\text{ mol/L} \end{aligned}$$

The concentration of sulfuric acid solution is 0.278 mol/L.

5. To determine the average volume of sodium hydroxide, $NaOH_{(aq)}$, used in the titration, you would probably take the average of the volumes used in Trials 1, 3, and 4. From the dark pink colour of the indicator, it appears as if the endpoint was exceeded in Trial 2. The volume of sodium hydroxide used in Trial 2 is also significantly more than the volume used in the other trials. The average volume of sodium hydroxide required to neutralize the unknown acid is 20.49 mL.

$$\begin{aligned} v_{NaOH} &= \frac{20.53\text{ mL} + 20.30\text{ mL} + 20.65\text{ mL}}{3} \\ &= 20.49\text{ mL} \end{aligned}$$

6. $HBr_{(aq)} + NaOH_{(aq)} \rightarrow NaBr_{(aq)} + H_2O_{(l)}$
   $2\ HBr_{(aq)} + Na_2CO_{3(aq)} \rightarrow 2\ NaBr_{(aq)} + CO_{2(g)} + H_2O_{(l)}$

Applying Inquiry Skills

7. Student answers may vary. One possible answer is provided.

Experimental Design

An experiment to determine the order of reactivity of the acids, from fastest to slowest, with magnesium involves adding a fixed mass of magnesium to a fixed volume of 0.10-mol/L acid solution in a test tube. Measure the time required for each piece of magnesium to disappear.

The independent variable in this investigation is the acid. The dependent variable is the time for the magnesium to disappear. The controlled variables are the mass of magnesium and the volume of acid solution used in each trial.

Making Connections

8. The low solubility of lime (calcium oxide, $CaO_{(s)}$) in water is advantageous for its use as a soil additive because the lime will not quickly dissolve and leach away. Thus, the lime remains in a primarily precipitated form in soil. A more soluble soil additive would be washed away quickly as water runs over or filters through the soil.