

## 4.5 Neutralization Reactions

### LEARNING OBJECTIVES

1. Identify an acid and a base.
2. Identify a neutralization reaction and predict its products.

In [Chapter 3 "Atoms, Molecules, and Ions"](#), [Section 3.5 "Acids"](#), we defined an acid as an ionic compound that contains  $\text{H}^+$  as the cation. This is slightly incorrect, but until additional concepts were developed, a better definition needed to wait. Now we can redefine an acid: an **acid** is any compound that increases the amount of hydrogen ion ( $\text{H}^+$ ) in an aqueous solution. The chemical opposite of an acid is a base. The equivalent definition of a base is that a **base** is a compound that increases the amount of hydroxide ion ( $\text{OH}^-$ ) in an aqueous solution. These original definitions were proposed by Arrhenius (the same person who proposed ion dissociation) in 1884, so they are referred to as the **Arrhenius definition** of an acid and a base, respectively.

You may recognize that, based on the description of a hydrogen atom, an  $\text{H}^+$  ion is a hydrogen atom that has lost its lone electron; that is,  $\text{H}^+$  is simply a proton. Do we really have bare protons moving about in aqueous solution? No. What is more likely is that the  $\text{H}^+$  ion has attached itself to one (or more) water molecule(s). To represent this chemically, we define the hydronium ion as  $\text{H}_3\text{O}^+$ , which represents an additional proton attached to a water molecule. We use the hydronium ion as the more logical way a hydrogen ion appears in an aqueous solution, although in many chemical reactions  $\text{H}^+$  and  $\text{H}_3\text{O}^+$  are treated equivalently.

The reaction of an acid and a base is called a neutralization reaction. Although acids and bases have their own unique chemistries, the acid and base cancel each other's chemistry to produce a rather innocuous substance—water. In fact, the general reaction between an acid and a base is

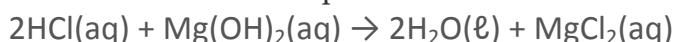
$$\text{acid} + \text{base} \rightarrow \text{water} + \text{salt}$$

where the term salt is generally used to define any ionic compound (soluble or insoluble) that is formed from a reaction between an acid and a base. (In chemistry,

the word *salt* refers to more than just table salt.) For example, the balanced chemical equation for the reaction between  $\text{HCl}(\text{aq})$  and  $\text{KOH}(\text{aq})$  is

$$\text{HCl}(\text{aq}) + \text{KOH}(\text{aq}) \rightarrow \text{H}_2\text{O}(\ell) + \text{KCl}(\text{aq})$$

where the salt is  $\text{KCl}$ . By counting the number of atoms of each element, we find that only one water molecule is formed as a product. However, in the reaction between  $\text{HCl}(\text{aq})$  and  $\text{Mg}(\text{OH})_2(\text{aq})$ , additional molecules of  $\text{HCl}$  and  $\text{H}_2\text{O}$  are required to balance the chemical equation:



Here, the salt is  $\text{MgCl}_2$ . (This is one of several reactions that take place when a type of antacid—a base—is used to treat stomach acid.)

### EXAMPLE 11

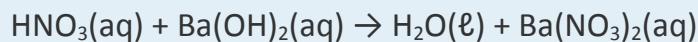
Write the neutralization reactions between each acid and base.

1.  $\text{HNO}_3(\text{aq})$  and  $\text{Ba}(\text{OH})_2(\text{aq})$
2.  $\text{H}_3\text{PO}_4(\text{aq})$  and  $\text{Ca}(\text{OH})_2(\text{aq})$

Solution

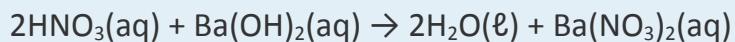
First, we will write the chemical equation with the formulas of the reactants and the expected products; then we will balance the equation.

1. The expected products are water and barium nitrate, so the initial chemical reaction is



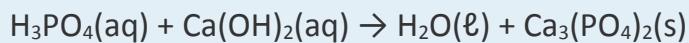
To balance the equation, we need to realize that there will be two  $\text{H}_2\text{O}$  molecules, so two  $\text{HNO}_3$  molecules are required:



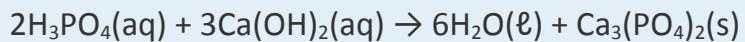


This chemical equation is now balanced.

2. The expected products are water and calcium phosphate, so the initial chemical equation is



According to the solubility rules,  $\text{Ca}_3(\text{PO}_4)_2$  is insoluble, so it has an (s) phase label. To balance this equation, we need two phosphate ions and three calcium ions; we end up with six water molecules to balance the equation:

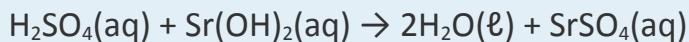


This chemical equation is now balanced.

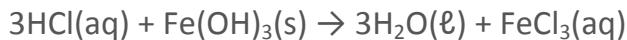
### *Test Yourself*

Write the neutralization reaction between  $\text{H}_2\text{SO}_4(\text{aq})$  and  $\text{Sr}(\text{OH})_2(\text{aq})$ .

### *Answer*



Neutralization reactions are one type of chemical reaction that proceeds even if one reactant is not in the aqueous phase. For example, the chemical reaction between  $\text{HCl}(\text{aq})$  and  $\text{Fe}(\text{OH})_3(\text{s})$  still proceeds according to the equation

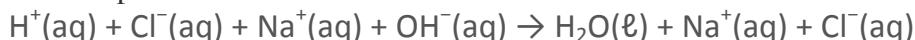


even though  $\text{Fe(OH)}_3$  is not soluble. When one realizes that  $\text{Fe(OH)}_3(\text{s})$  is a component of rust, this explains why some cleaning solutions for rust stains contain acids—the neutralization reaction produces products that are soluble and wash away. (Washing with acids like HCl is one way to remove rust and rust stains, but HCl must be used with caution!)

Complete and net ionic reactions for neutralization reactions will depend on whether the reactants and products are soluble, even if the acid and base react. For example, in the reaction of  $\text{HCl}(\text{aq})$  and  $\text{NaOH}(\text{aq})$ ,

$$\text{HCl}(\text{aq}) + \text{NaOH}(\text{aq}) \rightarrow \text{H}_2\text{O}(\ell) + \text{NaCl}(\text{aq})$$

the complete ionic reaction is

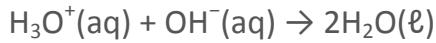


The  $\text{Na}^+(\text{aq})$  and  $\text{Cl}^-(\text{aq})$  ions are spectator ions, so we can remove them to have

$$\text{H}^+(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{H}_2\text{O}(\ell)$$

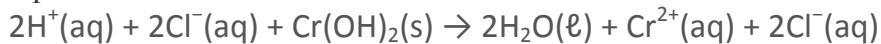
as the net ionic equation. If we wanted to write this in terms of the hydronium ion,

$\text{H}_3\text{O}^+(\text{aq})$ , we would write it as



With the exception of the introduction of an extra water molecule, these two net ionic equations are equivalent.

However, for the reaction between  $\text{HCl}(\text{aq})$  and  $\text{Cr(OH)}_2(\text{s})$ , because chromium(II) hydroxide is insoluble, we cannot separate it into ions for the complete ionic equation:



The chloride ions are the only spectator ions here, so the net ionic equation is

$$2\text{H}^+(\text{aq}) + \text{Cr(OH)}_2(\text{s}) \rightarrow 2\text{H}_2\text{O}(\ell) + \text{Cr}^{2+}(\text{aq})$$

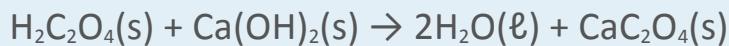
## EXAMPLE 12



Oxalic acid,  $\text{H}_2\text{C}_2\text{O}_4(\text{s})$ , and  $\text{Ca}(\text{OH})_2(\text{s})$  react very slowly. What is the net ionic equation between these two substances if the salt formed is insoluble? (The anion in oxalic acid is the oxalate ion,  $\text{C}_2\text{O}_4^{2-}$ .)

### Solution

The products of the neutralization reaction will be water and calcium oxalate:

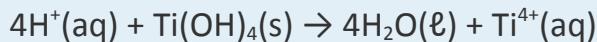


Because nothing is dissolved, there are no substances to separate into ions, so the net ionic equation is the equation of the three solids and one liquid.

### *Test Yourself*

What is the net ionic equation between  $\text{HNO}_3(\text{aq})$  and  $\text{Ti}(\text{OH})_4(\text{s})$ ?

### *Answer*



## KEY TAKEAWAYS

- The Arrhenius definition of an acid is a substance that increases the amount of  $\text{H}^+$  in an aqueous solution.
- The Arrhenius definition of a base is a substance that increases the amount of  $\text{OH}^-$  in an aqueous solution.
- Neutralization is the reaction of an acid and a base, which forms water and a salt.



- Net ionic equations for neutralization reactions may include solid acids, solid bases, solid salts, and water.

## EXERCISES

- What is the Arrhenius definition of an acid?
- What is the Arrhenius definition of a base?
- Predict the products of each acid-base combination listed. Assume that a neutralization reaction occurs.
  - HCl and KOH
  - $\text{H}_2\text{SO}_4$  and KOH
  - $\text{H}_3\text{PO}_4$  and  $\text{Ni}(\text{OH})_2$
- Predict the products of each acid-base combination listed. Assume that a neutralization reaction occurs.
  - HBr and  $\text{Fe}(\text{OH})_3$
  - $\text{HNO}_2$  and  $\text{Al}(\text{OH})_3$
  - $\text{HClO}_3$  and  $\text{Mg}(\text{OH})_2$
- Write a balanced chemical equation for each neutralization reaction in Exercise 3.
- Write a balanced chemical equation for each neutralization reaction in Exercise 4.

7. Write a balanced chemical equation for the neutralization reaction between each given acid and base. Include the proper phase labels.

- $\text{HI(aq)} + \text{KOH(aq)} \rightarrow ?$
- $\text{H}_2\text{SO}_4(\text{aq}) + \text{Ba(OH)}_2(\text{aq}) \rightarrow ?$

8. Write a balanced chemical equation for the neutralization reaction between each given acid and base. Include the proper phase labels.

- $\text{HNO}_3(\text{aq}) + \text{Fe(OH)}_3(\text{s}) \rightarrow ?$
- $\text{H}_3\text{PO}_4(\text{aq}) + \text{CsOH(aq)} \rightarrow ?$

9. Write the net ionic equation for each neutralization reaction in Exercise 7.

10. Write the net ionic equation for each neutralization reaction in Exercise 8.

11. Write the complete and net ionic equations for the neutralization reaction between  $\text{HClO}_3(\text{aq})$  and  $\text{Zn(OH)}_2(\text{s})$ . Assume the salt is soluble.

12. Write the complete and net ionic equations for the neutralization reaction between  $\text{H}_2\text{C}_2\text{O}_4(\text{s})$  and  $\text{Sr(OH)}_2(\text{aq})$ . Assume the salt is insoluble.

13. Explain why the net ionic equation for the neutralization reaction between  $\text{HCl(aq)}$  and  $\text{KOH(aq)}$  is the same as the net ionic equation for the neutralization reaction between  $\text{HNO}_3(\text{aq})$  and  $\text{RbOH}$ .

14. Explain why the net ionic equation for the neutralization reaction between  $\text{HCl(aq)}$  and  $\text{KOH(aq)}$  is different from the net ionic equation for the neutralization reaction between  $\text{HCl(aq)}$  and  $\text{AgOH}$ .

15. Write the complete and net ionic equations for the neutralization reaction between HCl(aq) and KOH(aq) using the hydronium ion in place of H<sup>+</sup>.

What difference does it make when using the hydronium ion?

16. Write the complete and net ionic equations for the neutralization reaction between HClO<sub>3</sub>(aq) and Zn(OH)<sub>2</sub>(s) using the hydronium ion in place of H<sup>+</sup>.

Assume the salt is soluble. What difference does it make when using the hydronium ion?

## ANSWERS

1. An Arrhenius acid increases the amount of H<sup>+</sup> ions in an aqueous solution.

3. a. KCl and H<sub>2</sub>O

b. K<sub>2</sub>SO<sub>4</sub> and H<sub>2</sub>O

c. Ni<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub> and H<sub>2</sub>O

5. a. HCl + KOH → KCl + H<sub>2</sub>O

b. H<sub>2</sub>SO<sub>4</sub> + 2KOH → K<sub>2</sub>SO<sub>4</sub> + 2H<sub>2</sub>O

c. 2H<sub>3</sub>PO<sub>4</sub> + 3Ni(OH)<sub>2</sub> → Ni<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub> + 6H<sub>2</sub>O

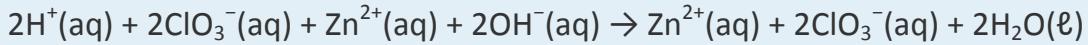
7. a. HI(aq) + KOH(aq) → KCl(aq) + H<sub>2</sub>O(l)

b. H<sub>2</sub>SO<sub>4</sub>(aq) + Ba(OH)<sub>2</sub>(aq) → BaSO<sub>4</sub>(s) + 2H<sub>2</sub>O(l)

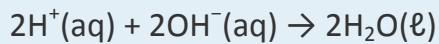
9 a. H<sup>+</sup>(aq) + OH<sup>-</sup>(aq) → H<sub>2</sub>O(l)

b. 2H<sup>+</sup>(aq) + SO<sub>4</sub><sup>2-</sup>(aq) + Ba<sup>2+</sup>(aq) + 2OH<sup>-</sup>(aq) → BaSO<sub>4</sub>(s) + 2H<sub>2</sub>O(l)

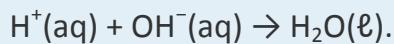
11. Complete ionic equation:



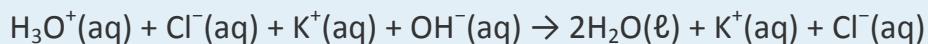
Net ionic equation:



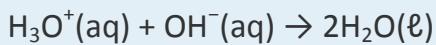
13. Because the salts are soluble in both cases, the net ionic reaction is just



15. Complete ionic equation:



Net ionic equation:



The difference is simply the presence of an extra water molecule as a product.

