SECTION 8.1

Understanding Reactions in Aqueous Solutions

Key Terms

- Precipitation
- Precipitate
- Precipitation reaction
- Strong electrolyte
- Soluble solid
- Insoluble solid (slightly soluble solid)
- Molecular equation
- Complete ionic equation
- Spectator ions
- Net ionic equation

Objectives

- *To learn about some of the factors that cause reactions to occur*
- *To learn to identify the solid that forms in a precipitation reaction*
- *To learn to write molecular, complete ionic, and net ionic equations*

A. Predicting Whether a Reaction Will Occur

In this text we have already seen many chemical reactions. Now let's consider an important question: Why does a chemical reaction occur? What causes reactants to "want" to form products? As chemists have studied reactions, they have recognized several "tendencies" in reactants that drive them to form products. That is, there are several "driving forces" that pull reactants toward products—changes that tend to make reactions go in the direction of the arrow. The most common of these driving forces are

- Formation of a solid
- Transfer of electrons
- Formation of water
- Formation of a gas

When two or more chemicals are brought together, if any of these things can occur, a chemical change (a reaction) is likely to take place. Accordingly, when we are confronted with a set of reactants and want to predict whether a reaction will occur and what products might form, we will consider these driving forces. They will help us organize our thoughts as we encounter new reactions.

Active Reading Question

Provide an example for each of the driving forces.

B. Reactions in Which a Solid Forms

One driving force for a chemical reaction is the formation of a solid, a process called **precipitation**. The solid that forms is called a **precipitate**, and the reaction is known as a **precipitation reaction**. For example, when an aqueous (water) solution of potassium chromate, $K_2CrO_4(aq)$, which is yellow, is added to a colorless aqueous solution containing barium nitrate, $Ba(NO_3)_2(aq)$, a yellow solid forms (see **Figure 8.1**). The fact that a solid forms tells us that a reaction—a chemical change—has occurred. That is, we have a situation where

Reactants $\rightarrow$ Products

What is the equation that describes this chemical change? To write the equation, we must decipher the identities of the reactants and products. The reactants have already been described: $K_2CrO_4(aq)$ and $Ba(NO_3)_2(aq)$. Is there some way in which we can predict the identities of the products? What is the yellow solid? The best way to predict the identity of this solid is to first *consider what products are possible.* To do this we need to know what chemical species are present in the solution that results when the reactant solutions are mixed. First, let's think about the nature of each reactant in an aqueous solution.

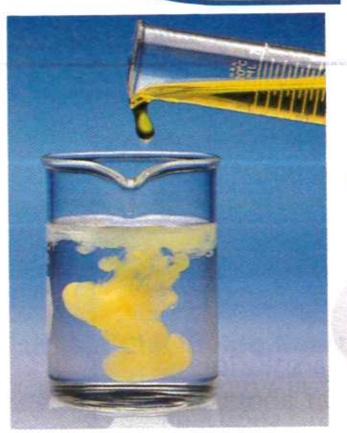


Figure 8.1
The precipitation reaction that occurs when yellow potassium chromate, $K_2CrO_4(aq)$, is mixed with a colorless barium nitrate solution, $Ba(NO_3)_2(aq)$

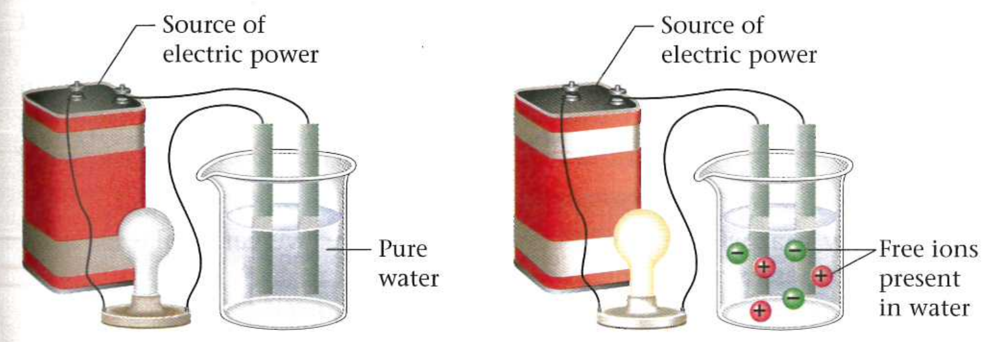
Precipitation
The formation of a solid in a chemical reaction

Precipitate
The solid that forms in a precipitation reaction

Precipitation reaction
A reaction in which a solid forms and separates from the solution

What Happens When an Ionic Compound Dissolves in Water?

The designation $Ba(NO_3)_2(aq)$ means that barium nitrate (a white solid) has been dissolved in water. Note from its formula that barium nitrate contains the Ba^{2+} and NO_3^- ions. *In virtually every case when a solid containing ions dissolves in water, the ions separate* and move around independently. We say that the ions of the solid *dissociate* when the solid dissolves in water. That is, $Ba(NO_3)_2(aq)$ does not contain $Ba(NO_3)_2$ units. Rather, it contains separated Ba^{2+} and NO_3^- ions. In the solution there are two NO_3^- ions for every Ba^{2+} ion. Chemists know that separated ions are present in this solution because it is an excellent conductor of electricity (see **Figure 8.2**). Pure water does not conduct an electric current. Ions must be present in water for a current to flow.



(a) Pure water does not conduct an electric current. The lamp does not light.

(b) When an ionic compound is dissolved in water, current flows and the lamp lights.

Figure 8.2
Electrical conductivity of aqueous solutions. The result of this experiment is strong evidence that ionic compounds dissolved in water exist in the form of separated ions.

When each unit of a substance that dissolves in water produces separated ions, the substance is called a **strong electrolyte**. Barium nitrate is a strong electrolyte in water, because each $Ba(NO_3)_2$ unit produces the separated ions (Ba^{2+}, NO_3^-, NO_3^-).

$$Ba(NO_3)_2(s) \xrightarrow{H_2O} Ba^{2+}(aq) + 2NO_3^-(aq)$$

Strong electrolyte
A substance that dissolves in water by dissociating completely into ions

Similarly, aqueous K_2CrO_4 also behaves as a strong electrolyte. Potassium chromate contains the K^+ and CrO_4^{2-} ions, so an aqueous solution of potassium chromate (which is prepared by dissolving solid K_2CrO_4 in water) contains these separated ions.

$$K_2CrO_4(s) \xrightarrow{H_2O} 2K^+(aq) + CrO_4^{2-}(aq)$$

Information

Note that the H_2O over the arrow here indicates that the substance is being dissolved in water.

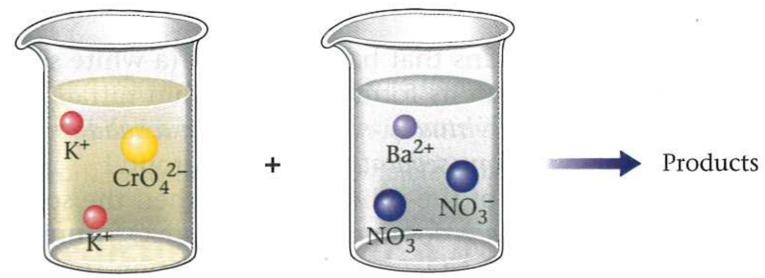
That is, $K_2CrO_4(aq)$ does not contain K_2CrO_4 units but instead contains K^+ cations and CrO_4^{2-} anions, which move around independently. (There are two K^+ ions for each CrO_4^{2-} ion.) The idea introduced here is very important:

When ionic compounds dissolve, the resulting solution contains the separated ions.

Therefore, we can represent the mixing of $K_2CrO_4(aq)$ and $Ba(NO_3)_2(aq)$ in two ways. We usually write these reactants as:

$$K_2CrO_4(aq) + Ba(NO_3)_2(aq) \rightarrow \text{Products}$$

However, a more accurate representation of the situation is:



$K_2CrO_4(aq)$
Ions separate when the solid dissolves.

$Ba(NO_3)_2(aq)$
Ions separate when the solid dissolves.

We can express this information in equation form as follows:

$$2K^+(aq) + CrO_4^{2-}(aq) + Ba^{2+}(aq) + 2NO_3^-(aq) \rightarrow \text{Products}$$

The ions in $K_2CrO_4(aq)$ — The ions in $Ba(NO_3)_2(aq)$

Thus the *mixed solution* contains four types of ions: K^+, CrO_4^{2-}, Ba^{2+}, and NO_3^-. Now that we know what the reactants are, we can make some educated guesses about the possible products.

How to Decide What Products Form

Which of these ions combine to form the yellow solid observed when the original solutions are mixed? This is not an easy question to answer. Even an experienced chemist is not sure what will happen in a new reaction. The chemist tries to think of the various possibilities, considers the likelihood of each possibility, and then makes a prediction (an educated guess). Only after identifying each product experimentally can the chemist be sure what reaction actually has taken place. However, an educated guess is very useful because it indicates what kinds of products are most likely. It gives us a place to start. So the best way to proceed is first to think of the various possibilities and then to decide which of them is most likely.

Possible Products What are the possible products of the reaction between $K_2CrO_4(aq)$ and $Ba(NO_3)_2(aq)$ or, more accurately, what reaction can occur among the ions K^+, CrO_4^{2-}, Ba^{2+}, and NO_3^-? We already know some things that will help us decide.

> A solid compound must have a zero net charge. This means that the product of our reaction must contain both anions and cations (negative and positive ions).

For example, K^+ and Ba^{2+} could not combine to form the solid because such a solid would have a positive charge. Similarly, CrO_4^{2-} and NO_3^- could not combine to form a solid because that solid would have a negative charge.

Something else that will help us is an observation that chemists have made by examining many compounds: *most ionic materials contain only two types of ions*—one type of cation and one type of anion. This idea is illustrated by the following compounds (among many others):

Ionic Materials

Compound	Cation	Anion
$NaCl$	Na^+	Cl^-
KOH	K^+	OH^-
Na_2SO_4	Na^+	SO_4^{2-}
NH_4Cl	NH_4^+	Cl^-
Na_2CO_3	Na^+	CO_3^{2-}

All the possible combinations of a cation and an anion to form uncharged compounds from among the ions K^+, CrO_4^{2-}, Ba^{2+}, and NO_3^- are shown below:

	NO_3^-	CrO_4^{2-}
K^+	KNO_3	K_2CrO_4
Ba^{2+}	$Ba(NO_3)_2$	$BaCrO_4$

So the compounds in red *might* be the solid.

Which of these possibilities is most likely to represent the yellow solid? We know it's not K_2CrO_4 or $Ba(NO_3)_2$; these are the reactants. They were present (dissolved) in the separate solutions that were mixed initially. The only real possibilities are KNO_3 and $BaCrO_4$. To decide which of these is more likely to represent the yellow solid, we need more facts. An experienced chemist, for example, knows that KNO_3 is a white solid. On the other hand, the CrO_4^{2-} ion is yellow. Therefore, the yellow solid must be $BaCrO_4$.

We have determined that one product of the reaction between $K_2CrO_4(aq)$ and $Ba(NO_3)_2(aq)$ is $BaCrO_4(s)$, but what happened to the K^+ and NO_3^- ions? The answer is that these ions are left dissolved in the solution. That is, KNO_3 does not form a solid when the K^+ and NO_3^- ions are present in water. In other words, if we took the white solid $KNO_3(s)$ and put it in water, it would

CHEMISTRY IN YOUR WORLD

Consumer Connection

Instant Cooking—On Demand

Can you think of foods you've recently prepared that were ready to go—except for adding water? From breakfast through dessert, chemists have found ways to prepare mixes that stay unreacted and ready to use on our shelves. All we need to do is place them in a bowl, add water, and cook! Why don't the ingredients react in the box?

Most of the ingredients used in mixes are solids. We've already seen that solids don't usually react until they are dissolved in water. So as long as moisture is kept out of the mix, it will remain unreacted.

Sometimes manufacturers also dehydrate ingredients such as milk and eggs so they can be stored in unreactive form in the mix as well.

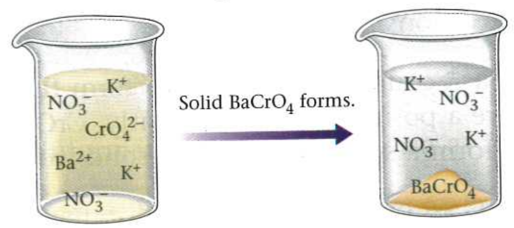
Flavored gelatin

totally dissolve (the white solid would "disappear," yielding a colorless solution). So when we mix $K_2CrO_4(aq)$ and $Ba(NO_3)_2(aq)$, $BaCrO_4(s)$ forms but KNO_3 is left behind in solution—we write it as $KNO_3(aq)$. If we poured the mixture through a filter to remove the solid $BaCrO_4$ and then evaporated all of the water, we would obtain the white solid KNO_3.

After all this thinking, we can finally write the unbalanced equation for the precipitation reaction.

$$K_2CrO_4(aq) + Ba(NO_3)_2(aq) \rightarrow BaCrO_4(s) + KNO_3(aq)$$

We can represent this reaction in pictures as follows:



Note that the K^+ and NO_3^- ions are not involved in the chemical change. They are present in the solution before and after the reaction.

Active Reading Question

How do we know that K_2CrO_4 and $Ba(NO_3)_2$ are not the solids?

Using Solubility Rules

In our example above we were finally able to identify the products of the reaction by using two types of chemical knowledge:

1. **Facts:** Knowing the colors of the compounds was very helpful.
2. **Concepts:** Knowing the concept that solids always have a net charge of zero was also important.

These two kinds of knowledge allowed us to make a good guess about the identity of the solid that formed. As you continue to study chemistry, you will see that a balance of factual and conceptual knowledge is always required. You must both *memorize* important facts and *understand* crucial concepts to succeed.

information

Solids must contain both anions and cations in the relative numbers necessary to produce zero net charge.

Does a Solid Always Form? In the present case we are dealing with a reaction in which an ionic solid forms—that is, a process in which ions that are dissolved in water combine to give a solid. We know that for a solid to form, both positive and negative ions must be present in relative numbers that give zero net charge. However, oppositely charged ions in water do not always react to form a solid, as we have seen for K^+ and NO_3^-. In addition, Na^+ and Cl^- can coexist in water in very large numbers with no formation of solid NaCl. In other words, when solid NaCl (common salt) is placed in water, it dissolves—the white solid "disappears" as the Na^+ and Cl^- ions are dispersed throughout the water. The following two statements, then, are really saying the same thing:

1. Solid NaCl is very soluble in water.
2. Solid NaCl does not form when one solution containing Na^+ is mixed with another solution containing Cl^-.

Predicting Precipitates To predict whether a given pair of dissolved ions will form a solid when mixed, we must know some facts about the solubilities of various types of ionic compounds. In this text we will use the term **soluble solid** to mean a solid that readily dissolves in water; the solid "disappears" as the ions are dispersed in the water. The terms **insoluble solid** and **slightly soluble solid** are taken to mean the same thing: a solid where such a tiny amount dissolves in water that it is undetectable with the naked eye. The solubility information about common solids that is summarized in **Table 8.1** is based on observations of the behavior of many compounds. This is factual knowledge that you will need to predict what will happen in chemical reactions where a solid might form. This information is summarized in **Figure 8.3.**

Soluble solid
A solid that readily dissolves in water

Insoluble solid (slightly soluble solid)
A solid that dissolves to such a small degree that it is not detectable to the naked eye

Table 8.1

General Rules for Solubility of Ionic Compounds (Salts) in Water at 25 °C

1. Most nitrate (NO_3^-) salts are soluble.
2. Most salts of Na^+, K^+, and NH_4^+ are soluble.
3. Most chloride salts are soluble. Notable exceptions are AgCl, $PbCl_2$, and Hg_2Cl_2.
4. Most sulfate salts are soluble. Notable exceptions are $BaSO_4$, $PbSO_4$, and $CaSO_4$.
5. Most hydroxide compounds are only slightly soluble.* The important exceptions are NaOH and KOH. $Ba(OH)_2$ and $Ca(OH)_2$ are moderately soluble.
6. Most sulfide (S^{2-}), carbonate (CO_3^{2-}), and phosphate (PO_4^{3-}) salts are only slightly soluble.*

*The terms *insoluble* and *slightly soluble* really mean the same thing: such a tiny amount dissolves that it is not possible to detect it with the naked eye.

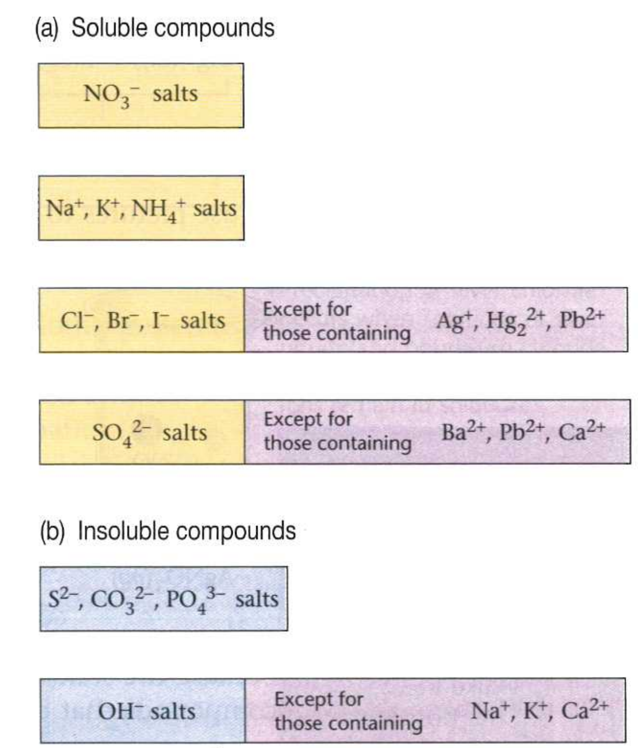


Figure 8.3
Solubilities of common compounds

Notice that in Table 8.1 and Figure 8.3 the term *salt* is used to mean *ionic compound*. Many chemists use the terms *salt* and *ionic compound* interchangeably. In Example 8.1, we will illustrate how to use the solubility rules to predict the products of reactions among ions.

information

In predicting what reaction will occur when ions are mixed in water, focus on the ions that are in solution before any reaction occurs.

EXAMPLE 8.1

Identifying Precipitates in Reactions Where a Solid Forms

information

$AgNO_3$ is usually called "silver nitrate" rather than "silver(I) nitrate" because silver forms only Ag^+.

When an aqueous solution of silver nitrate is added to an aqueous solution of potassium chloride, a white solid forms. Identify the white solid and write the balanced equation for the reaction that occurs.

Solution

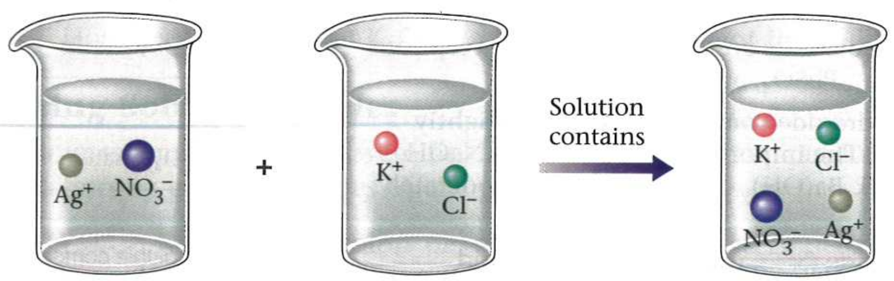
First let's write the equation for the reaction:

$$AgNO_3(aq) + KCl(aq) \rightarrow \text{White solid}$$

To answer the question "What is the white solid?" we must decide what ions are present in the mixed solution. Remember that *when ionic substances dissolve in water, the ions separate.* So we can write the equation

$$\underbrace{Ag^+(aq) + NO_3^-(aq)}_{\text{Ions in } AgNO_3(aq)} + \underbrace{K^+(aq) + Cl^-(aq)}_{\text{Ions in } KCl(aq)} \rightarrow \text{Products}$$

or use pictures to represent the ions present in the mixed solution before any reaction occurs.



information

Use a table like this to figure out the possible combinations.

	NO_3^-	Cl^-
Ag^+	$AgNO_3$	AgCl
K^+	KNO_3	KCl

Now we will consider what solid *might* form from this collection of ions. Because the solid must contain both positive and negative ions, the possible compounds that can be assembled from this collection of ions are

$AgNO_3$ AgCl KNO_3 KCl

$AgNO_3$ and KCl are the substances already dissolved in the reactant solutions, so we know that they do not represent the white solid product. We are left with two possibilities:

AgCl KNO_3

Another way to obtain these two possibilities is by *ion interchange*. This means that in the reaction of $AgNO_3(aq)$ and $KCl(aq)$, we take the cation from one reactant and combine it with the anion of the other reactant.

$$Ag^+ + NO_3^- + K^+ + Cl^- \rightarrow \text{Products}$$

Possible solid products

Ion interchange leads to the following possible solids:

AgCl or KNO_3

To decide whether AgCl or KNO_3 is the white solid, we need the solubility rules (Table 8.1).

Rule 2 states that most salts containing K^+ are soluble in water.

Rule 1 says that most nitrate salts (those containing NO_3^-) are soluble. So the salt KNO_3 is water-soluble. That is, when K^+ and NO_3^- are mixed in water, a solid (KNO_3) does *not* form.

Rule 3 states that although most chloride salts (salts that contain Cl^-) are soluble, AgCl is an exception. That is, AgCl(*s*) is insoluble in water.

Thus the white solid must be AgCl. Now we can write

$$AgNO_3(aq) + KCl(aq) \rightarrow AgCl(s) + ?$$

What is the other product?

To form AgCl(*s*), we have used the Ag^+ and Cl^- ions:

$$Ag^+(aq) + NO_3^-(aq) + K^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$$

This leaves the K^+ and NO_3^- ions. What do they do? Nothing. Because KNO_3 is very soluble in water (rules 1 and 2), the K^+ and NO_3^- ions remain separate in the water; the KNO_3 remains dissolved and we represent it as $KNO_3(aq)$. We can now write the full equation:

$$AgNO_3(aq) + KCl(aq) \rightarrow AgCl(s) + KNO_3(aq)$$

Figure 8.4 shows the precipitation of AgCl(*s*) that occurs when this reaction takes place. In graphic form, the reaction is

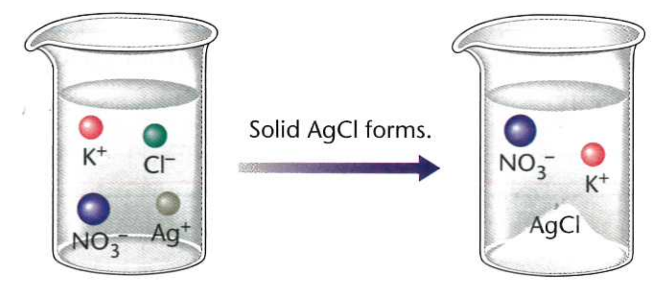


Figure 8.4
Precipitation of silver chloride occurs when solutions of silver nitrate and potassium chloride are mixed. The K^+ and NO_3^- ions remain in solution.

Let's Review

How to Predict Precipitates When Solutions of Two Ionic Compounds Are Mixed

Step 1 Write the reactants as they actually exist before any reaction occurs. Remember that when a salt dissolves, its ions separate.

Step 2 Consider the various solids that could form. To do this, simply *exchange the anions* of the added salts.

Step 3 Use the solubility rules (Table 8.1) to decide whether a solid forms and, if so, to predict the identity of the solid.

EXAMPLE 8.2

Using Solubility Rules to Predict the Products of Reactions

Using the solubility rules in Table 8.1, predict what will happen when the following solutions are mixed. Write the balanced equation for any reaction that occurs.

a. $KNO_3(aq)$ and $BaCl_2(aq)$ **c.** $KOH(aq)$ and $Fe(NO_3)_3(aq)$

b. $Na_2SO_4(aq)$ and $Pb(NO_3)_2(aq)$

Solution

a. $KNO_3(aq)$ and $BaCl_2(aq)$

Step 1 $KNO_3(aq)$ represents an aqueous solution obtained by dissolving solid KNO_3 in water to give the ions $K^+(aq)$ and $NO_3^-(aq)$. Likewise, $BaCl_2(aq)$ is a solution formed by dissolving solid $BaCl_2$ in water to produce $Ba^{2+}(aq)$ and $Cl^-(aq)$. When these two solutions are mixed, the following ions will be present:

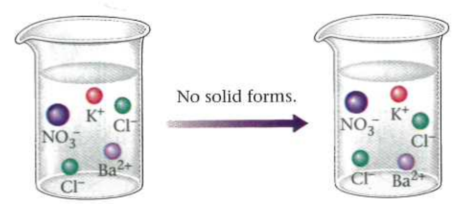
K^+, NO_3^-, (From $KNO_3(aq)$) Ba^{2+}, Cl^- (From $BaCl_2(aq)$)

Step 2 To get the possible products, we exchange the anions.

K^+ NO_3^- Ba^{2+} Cl^-

This yields the possibilities KCl and $Ba(NO_3)_2$. These are the solids that *might* form. Notice that two NO_3^- ions are needed to balance the 2+ charge on Ba^{2+}.

Step 3 The rules listed in Table 8.1 indicate that both KCl and $Ba(NO_3)_2$ are soluble in water. So no precipitate forms when $KNO_3(aq)$ and $BaCl_2(aq)$ are mixed. All of the ions remain dissolved in the solution. This means that no reaction takes place. That is, no chemical change occurs.



b. $Na_2SO_4(aq)$ and $Pb(NO_3)_2(aq)$

Step 1 The following ions are present in the mixed solution before any reaction occurs:

Na^+, SO_4^{2-}, (From $Na_2SO_4(aq)$) Pb^{2+}, NO_3^- (From $Pb(NO_3)_2(aq)$)

Step 2 Exchanging anions as follows:

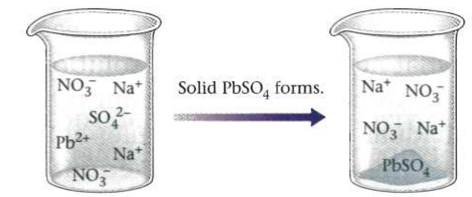
Na^+ SO_4^{2-} Pb^{2+} NO_3^-

yields the *possible* solid products $PbSO_4$ and $NaNO_3$.

Step 3 Using Table 8.1, we see that $NaNO_3$ is soluble in water (rules 1 and 2) but that $PbSO_4$ is only slightly soluble (rule 4). Thus, when these solutions are mixed, solid $PbSO_4$ forms. The balanced reaction is

$$Na_2SO_4(aq) + Pb(NO_3)_2(aq) \rightarrow PbSO_4(s) + \underbrace{2NaNO_3(aq)}_{\text{Remains dissolved}}$$

which can be represented as



c. $KOH(aq)$ and $Fe(NO_3)_3(aq)$

Step 1 The ions present in the mixed solution before any reaction occurs are

K^+, OH^-, (From $KOH(aq)$) Fe^{3+}, NO_3^- (From $Fe(NO_3)_3(aq)$)

Step 2 Exchanging anions as follows:

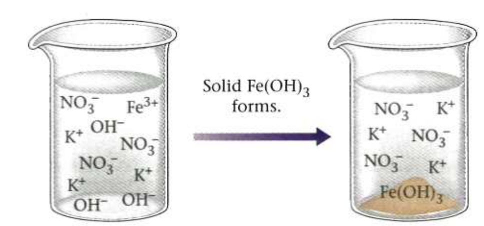
K^+ OH^- Fe^{3+} NO_3^-

yields the possible solid products KNO_3 and $Fe(OH)_3$.

Step 3 Rules 1 and 2 (Table 8.1) state that KNO_3 is soluble, whereas $Fe(OH)_3$ is only slightly soluble (rule 5). Thus, when these solutions are mixed, solid $Fe(OH)_3$ forms. The balanced equation for the reaction is

$$3KOH(aq) + Fe(NO_3)_3(aq) \rightarrow Fe(OH)_3(s) + 3KNO_3(aq)$$

which can be represented as



Practice Problem • Exercise 8.2

Predict whether a solid will form when the following pairs of solutions are mixed. If so, identify the solid and write the balanced equation for the reaction.

a. $Ba(NO_3)_2(aq)$ and $NaCl(aq)$

b. $Na_2S(aq)$ and $Cu(NO_3)_2(aq)$

c. $NH_4Cl(aq)$ and $Pb(NO_3)_2(aq)$

C. Describing Reactions in Aqueous Solutions

Molecular equation
A chemical equation showing the complete (undissociated) forms of all reactants and products

Complete ionic equation
A chemical equation for a reaction in solution representing all strong electrolytes as ions

Spectator ion
An ion present in solution that does not participate in a reaction

Net ionic equation
A chemical equation for a reaction in solution showing only those components that are directly involved in the reaction. Strong electrolytes are represented as ions.

Much important chemistry, including virtually all of the reactions that make life possible, occurs in aqueous solutions. We will now consider the types of equations used to represent reactions that occur in water. For example, as we saw earlier, when we mix aqueous potassium chromate with aqueous barium nitrate, a reaction occurs to form solid barium chromate and dissolved potassium nitrate. One way to represent this reaction is by the equation

$$K_2CrO_4(aq) + Ba(NO_3)_2(aq) \rightarrow BaCrO_4(s) + 2KNO_3(aq)$$

This is called the **molecular equation** for the reaction; it shows the complete formulas of all reactants and products. However, although this equation shows the reactants and products of the reaction, it does not give a very clear picture of what actually occurs in solution. As we have seen, aqueous solutions of potassium chromate, barium nitrate, and potassium nitrate contain the individual ions, not molecules as is implied by the molecular equation. Thus the **complete ionic equation**,

$$\underbrace{2K^+(aq) + CrO_4^{2-}(aq)}_{\text{Ions from } K_2CrO_4} + \underbrace{Ba^{2+}(aq) + 2NO_3^-(aq)}_{\text{Ions from } Ba(NO_3)_2} \rightarrow BaCrO_4(s) + 2K^+(aq) + 2NO_3^-(aq)$$

better represents the actual forms of the reactants and products in solution. *In a complete ionic equation, all substances that are strong electrolytes are represented as ions.* Notice that $BaCrO_4$ is not written as the separate ions, because it is present as a solid; it is not dissolved.

The complete ionic equation reveals that only some of the ions participate in the reaction. Notice that the K^+ and NO_3^- ions are present in solution both before and after the reaction. Ions such as these, which do not participate directly in a reaction in solution, are called **spectator ions**. The ions that participate in this reaction are the Ba^{2+} and CrO_4^{2-} ions, which combine to form solid $BaCrO_4$:

$$Ba^{2+}(aq) + CrO_4^{2-}(aq) \rightarrow BaCrO_4(s)$$

This equation, called the **net ionic equation**, includes only those components that are directly involved in the reaction. Chemists usually write the net ionic equation for a reaction in solution, because it gives the actual forms of the reactants and products and includes only the species that undergo a change.

information

A strong electrolyte is a substance that completely breaks apart into ions when dissolved in water. The resulting solution readily conducts an electric current.

Active Reading Questions

1. **A solution of lead(II) nitrate is reacted with a solution of potassium iodide. Write a molecular equation, complete ionic equation, and net ionic equation for this reaction.**
2. **According to the solubility rules, which ions are generally spectator ions?**

Let's Review

Types of Equations for Reactions in Aqueous Solutions

Three types of equations are used to describe reactions in solutions.

- The *molecular equation* shows the overall reaction but not necessarily the actual forms of the reactants and products in solution.
- The *complete ionic equation* represents all reactants and products that are strong electrolytes as ions. All reactants and products are included.
- The *net ionic equation* includes only those components that undergo a change. Spectator ions are not included.

A Closer Look

In Example 8.2 we considered the reaction between aqueous solutions of lead nitrate and sodium sulfate. The molecular equation for this reaction is

$$Pb(NO_3)_2(aq) + Na_2SO_4(aq) \rightarrow PbSO_4(s) + 2NaNO_3(aq)$$

Because any ionic compound that is dissolved in water is present as the separated ions, we can write the complete ionic equation as follows:

$$Pb^{2+}(aq) + 2NO_3^-(aq) + 2Na^+(aq) + SO_4^{2-}(aq) \rightarrow PbSO_4(s) + 2Na^+(aq) + 2NO_3^-(aq)$$

The $PbSO_4$ is not written as separate ions because it is present as a solid. The ions that take part in the chemical change are the Pb^{2+} and the SO_4^{2-} ions, which combine to form solid $PbSO_4$. Thus the net ionic equation is

$$Pb^{2+}(aq) + SO_4^{2-}(aq) \rightarrow PbSO_4(s)$$

The Na^+ and NO_3^- ions do not undergo any chemical change; they are spectator ions.

information

The net ionic equation includes only those components that undergo a change in the reaction.

Active Reading Question

What is the advantage of writing net ionic equations for chemical reactions?

EXAMPLE 8.3

Writing Equations for Reactions

For each of the following reactions, write the molecular equation, the complete ionic equation, and the net ionic equation.

a. Aqueous sodium chloride is added to aqueous silver nitrate to form solid silver chloride plus aqueous sodium nitrate.

b. Aqueous potassium hydroxide is mixed with aqueous iron(III) nitrate to form solid iron(III) hydroxide and aqueous potassium nitrate.

Solution

a. *Molecular equation:*

$$NaCl(aq) + AgNO_3(aq) \rightarrow AgCl(s) + NaNO_3(aq)$$

Complete ionic equation:

$$Na^+(aq) + Cl^-(aq) + Ag^+(aq) + NO_3^-(aq) \rightarrow AgCl(s) + Na^+(aq) + NO_3^-(aq)$$

Net ionic equation:

$$Cl^-(aq) + Ag^+(aq) \rightarrow AgCl(s)$$

b. *Molecular equation:*

$$3KOH(aq) + Fe(NO_3)_3(aq) \rightarrow Fe(OH)_3(s) + 3KNO_3(aq)$$

Complete ionic equation:

$$3K^+(aq) + 3OH^-(aq) + Fe^{3+}(aq) + 3NO_3^-(aq) \rightarrow Fe(OH)_3(s) + 3K^+(aq) + 3NO_3^-(aq)$$

Net ionic equation:

$$3OH^-(aq) + Fe^{3+}(aq) \rightarrow Fe(OH)_3(s)$$

Practice Problem • Exercise 8.3

For each of the following reactions, write the molecular equation, the complete ionic equation, and the net ionic equation.

a. Aqueous sodium sulfide is mixed with aqueous copper(II) nitrate to produce solid copper(II) sulfide and aqueous sodium nitrate.

b. Aqueous ammonium chloride and aqueous lead(II) nitrate react to form solid lead(II) chloride and aqueous ammonium nitrate.

CELEBRITY CHEMICAL Ammonia (NH_3)

Ammonia is a colorless gas with a strong odor that can be liquified at −34 °C. Ammonia (dissolved in water) is found in many household cleaning products.

Ammonia is manufactured by combining the elements nitrogen and hydrogen:

$$3H_2(g) + N_2(g) \rightarrow 2NH_3(g)$$

The major use of ammonia is as a fertilizer to furnish nitrogen atoms to growing plants. Approximately 30 *billion* pounds of ammonia are produced every year for this purpose. For use as a fertilizer, the ammonia is liquified (at high pressures) and stored in mobile tanks that can be pulled through the fields by a tractor. It is then injected into the ground to serve as an additional source of nitrogen for the crop.

A cross section showing how ammonia is injected into the soil to act as a fertilizer

HANDS-ON CHEMISTRY • MINI-LAB •

Forecast: Precipitation

Materials

- index cards (or flashcards from the Chapter 4 activities if available)

Procedure

1. Make two sets of flashcards. Put the name of an ion on one side and its symbol and charge on the other (use the cards from the Chapter 4 activities if you did them).

   Set A: all of the alkali and alkaline earth metals, and iron(II), iron(III), lead(II), and silver.

   Set B: all of the nonmetals from Groups 5A, 6A, and 7A, and the polyatomic ions listed in Table 4.4

2. Randomly pick one card from Set A and one card from Set B. Write the proper formula for the ionic compound made from these two ions, and name the compound.
3. Repeat step 2. Are both ionic compounds soluble? If so, go to step 4, if not, go back to step 2.
4. Use the two soluble ionic compounds as reactants. Write the names and formulas for the possible products of the reaction, along with the molecular equation and complete ionic equation. Is at least one of the products insoluble? If so, go to step 5. If not, go back to step 2.
5. Write the net ionic equation for the reaction. Go back to step 2 and continue this process until you have 5 net ionic equations.

SECTION 8.1 REVIEW QUESTIONS

1. What are the driving forces that indicate a chemical reaction is likely to occur?
2. Use the solubility rules in Table 8.1 or the information in Figure 8.3 to predict which of the following will be soluble in water:
   a. potassium nitrate
   b. zinc hydroxide
   c. calcium carbonate
   d. ammonium chloride
3. Consider two separate beakers, one containing an aqueous solution of hydrochloric acid, the second an aqueous solution of lead(II) nitrate.
   a. Draw a picture of each solution showing the ions present.
   b. Draw a picture after the solutions are mixed showing what is present.
   c. Predict the products for any reaction that occurs.
   d. Write a net ionic equation for the reaction.
4. How is a molecular equation different from a complete ionic equation?
5. What is a spectator ion and what happens to it in a net ionic equation?
6. Consider the following reaction: aqueous sodium sulfate is added to aqueous barium bromide to form solid barium sulfate and aqueous sodium bromide.
   a. Write the molecular equation.
   b. Write the complete ionic equation.
   c. List the spectator ions.
   d. Write the net ionic equation.

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SECTION 8.2

Other Reactions in Aqueous Solutions

Key Terms

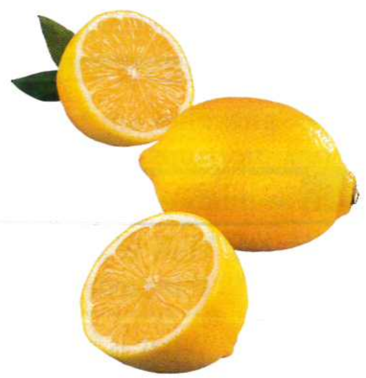
- Acid
- Strong acids
- Base
- Strong bases
- Salt
- Oxidation–reduction reaction

Objectives

- *To learn about the reactions between strong acids and strong bases*
- *To learn about the reaction between a metal and a nonmetal*
- *To understand how electron transfer produces a chemical reaction*

A. Reactions That Form Water: Acids and Bases

In this section we encounter two very important classes of compounds: acids and bases. Acids were first associated with the sour taste of citrus fruits. In fact, the word *acid* comes from the Latin word *acidus*, which means "sour." Vinegar tastes sour because it is a dilute solution of acetic acid; citric acid is responsible for the sour taste of a lemon. Bases, sometimes called *alkalis*, are characterized by their bitter taste and slippery feel, like wet soap. Most commercial preparations for unclogging drains are highly basic.



information

Don't taste chemicals!

Acids have been known for hundreds of years. For example, the *mineral acids* sulfuric acid, H_2SO_4, and nitric acid, HNO_3, so named because they were originally obtained by the treatment of minerals, were discovered around 1300. However, it was not until the late 1800s that the essential nature of acids was discovered by Svante Arrhenius, then a Swedish graduate student in physics.

Arrhenius Acids and Bases Arrhenius, who was trying to discover why only certain solutions could conduct an electric current, found that conductivity arose from the presence of ions. In his studies of solutions, Arrhenius observed that when the substances HCl, HNO_3, and H_2SO_4 were dissolved in water, they behaved as strong electrolytes. He suggested that this was the result of ionization reactions in water.

$$HCl \xrightarrow{H_2O} H^+(aq) + Cl^-(aq)$$

$$HNO_3 \xrightarrow{H_2O} H^+(aq) + NO_3^-(aq)$$

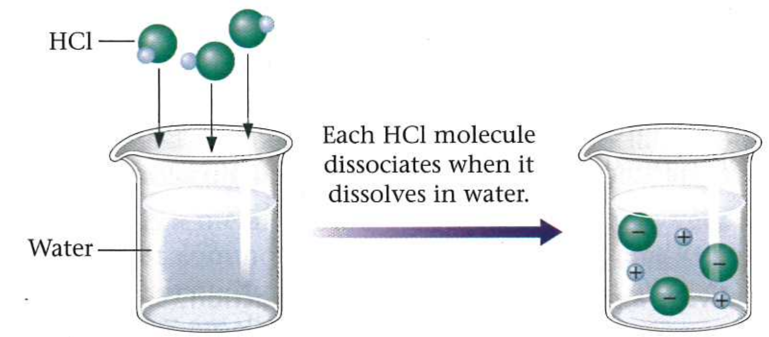
$$H_2SO_4 \xrightarrow{H_2O} H^+(aq) + HSO_4^-(aq)$$

information

The Arrhenius definition of an acid: a substance that produces H^+ ions in aqueous solution.

Arrhenius proposed that an **acid** *is a substance that produces H^+ ions (protons) when it is dissolved in water.*

Studies show that when HCl, HNO_3, and H_2SO_4 are placed in water, *virtually every molecule* dissociates to give ions. This means that when 100 molecules of HCl are dissolved in water, 100 H^+ ions and 100 Cl^- ions are produced. Virtually no HCl molecules exist in aqueous solution.



Because these substances are strong electrolytes that produce H^+ ions, they are called **strong acids**.

Strong acid
An acid that completely dissociates to produce H^+ ions in solution.

Strong base
A base that completely dissociates to produce OH^- ions in solution.

Arrhenius also found that *aqueous solutions that exhibit basic behavior* always contain hydroxide ions. He defined a **base** as a *substance that produces hydroxide ions (OH^-) in water*. The base most commonly used in the chemical laboratory is sodium hydroxide, NaOH, which contains Na^+ and OH^- ions and is very soluble in water. Sodium hydroxide, like all ionic substances, produces separated cations and anions when it is dissolved in water.

$$NaOH(s) \xrightarrow{H_2O} Na^+(aq) + OH^-(aq)$$

Although dissolved sodium hydroxide is usually represented as NaOH(*aq*), you should remember that the solution really contains separated Na^+ and OH^- ions. In fact, for every 100 units of NaOH dissolved in water, 100 Na^+ ions and 100 OH^- ions are produced.

Potassium hydroxide (KOH) has properties markedly similar to those of sodium hydroxide. It is very soluble in water and produces separated ions.

$$KOH(s) \xrightarrow{H_2O} K^+(aq) + OH^-(aq)$$

DID YOU KNOW

The Nobel Prize in Chemistry was awarded to Arrhenius in 1903 for his studies of solution conductivity.

Because these hydroxide compounds are strong electrolytes that contain OH^- ions, they are called **strong bases**.

When strong acids and strong bases (hydroxides) are mixed, the fundamental chemical change that always occurs is that H^+ ions react with OH^- ions to form water.

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

Water is a very stable compound, as evidenced by the abundance of it on the earth's surface. Therefore, when substances that can form water are mixed, there is a strong tendency for the reaction to occur. In particular, the hydroxide ion OH^- has a high affinity for the H^+ ion to produce water.

The tendency to form water is the second of the driving forces for reactions that we mentioned before. Any compound that produces OH^- ions in water reacts vigorously to form H_2O with any compound that can furnish H^+ ions. For example, the reaction between hydrochloric acid and aqueous sodium hydroxide is represented by the following molecular equation:

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

information

Hydrochloric acid is an aqueous solution that contains dissolved hydrogen chloride. It is a strong electrolyte.

Because HCl, NaOH, and NaCl exist as completely separated ions in water, the complete ionic equation for this reaction is

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

Notice that the Cl^- and Na^+ are spectator ions (they undergo no changes), so the net ionic equation is

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

Thus the only chemical change that occurs when these solutions are mixed is that water is formed from H^+ and OH^- ions.

Active Reading Question

What is always a product of an acid–base reaction?

EXAMPLE 8.4

Writing Equations for Acid–Base Reactions

Nitric acid is a strong acid. Write the molecular, complete ionic, and net ionic equations for the reaction of aqueous nitric acid and aqueous potassium hydroxide.

Solution

Molecular equation:

$$HNO_3(aq) + KOH(aq) \rightarrow H_2O(l) + KNO_3(aq)$$

Complete ionic equation:

$$H^+(aq) + NO_3^-(aq) + K^+(aq) + OH^-(aq) \rightarrow H_2O(l) + K^+(aq) + NO_3^-(aq)$$

Net ionic equation:

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

Note that K^+ and NO_3^- are spectator ions and that the formation of water is the driving force for this reaction.

There are two important things to note as we examine the reaction of hydrochloric acid with aqueous sodium hydroxide and the reaction of nitric acid with aqueous potassium hydroxide:

1. The net ionic equation is the same in both cases; water is formed.

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

2. Besides water, which is *always a product* of the reaction of an acid with OH^-, the second product is an ionic compound, which might precipitate or remain dissolved, depending on its solubility.

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

$$HNO_3(aq) + KOH(aq) \rightarrow H_2O(l) + KNO_3(aq)$$

Dissolved ionic compounds

Salt
An ionic compound

This ionic compound is called a **salt**. In the first case the salt is sodium chloride, and in the second case the salt is potassium nitrate. We can obtain these soluble salts in solid form (both are white solids) by evaporating the water.

Let's Review

Strong Acids and Strong Bases

The following points about strong acids and strong bases are particularly important.

- The common strong acids are aqueous solutions of HCl, HNO_3, and H_2SO_4.
- A strong acid is a substance that completely dissociates (ionizes) in water. (Each molecule breaks up into an H^+ ion plus an anion.)
- A strong base is a metal hydroxide compound that is very soluble in water. The most common strong bases are NaOH and KOH, which completely break up into separated ions (Na^+ and OH^- or K^+ and OH^-) when they are dissolved in water.
- The net ionic equation for the reaction of a strong acid and a strong base is always the same: it shows the production of water.

  $$H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$$
- In the reaction of a strong acid and a strong base, one product is always water and the other is always an ionic compound called a salt, which remains dissolved in the water. This salt can be obtained as a solid by evaporating the water.
- The reaction of H^+ and OH^- is often called an acid–base reaction, where H^+ is the acidic ion and OH^- is the basic ion.

information

Both strong acids and strong bases are strong electrolytes.

CELEBRITY CHEMICAL Calcium Carbonate ($CaCO_3$)

Calcium carbonate, which contains the Ca^{2+} and CO_3^{2-} ions, is very common in nature, occurring in eggshells, limestone, marble, seashells, and coral. The spectacular formations seen in limestone caves are also composed of calcium carbonate.

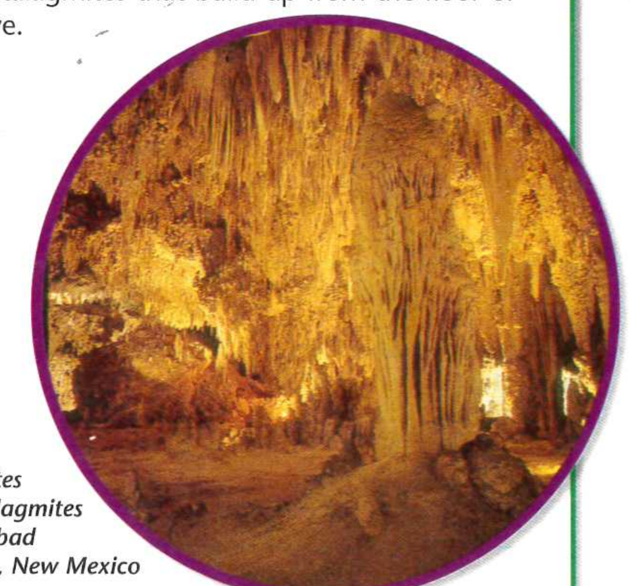
Limestone caves form when underground limestone deposits come in contact with water made acidic by dissolved carbon dioxide. When rainwater absorbs CO_2 from the atmosphere, the following reaction occurs:

$$CO_2(g) + H_2O(l) \rightarrow H^+(aq) + HCO_3^-(aq)$$

This reaction leads to the presence of H^+ in the groundwater. The acidic groundwater then causes the limestone (which is made of $CaCO_3$) to dissolve:

$$CaCO_3(s) + H^+(aq) \rightarrow Ca^{2+}(aq) + HCO_3^-(aq)$$

Underground caverns then form. In the process of dissolving the limestone and creating the cave, the water containing the dissolved $CaCO_3$ drips from the ceiling of the cave. As the water forms drops, it tends to lose some of the dissolved CO_2, which lowers the amount of H^+ present (by the reversal of the first reaction). This in turn leads to the reversal of the second reaction, which then reforms the solid $CaCO_3$. This process causes stalactites to "grow" from the ceiling of the cave. Water that drips to the floor before losing its dissolved CO_2 forms stalagmites that build up from the floor of the cave.



Stalactites and stalagmites in Carlsbad Caverns, New Mexico