11.3

1 FOCUS

Objectives

11.3.1 Describe the information found in a net ionic equation.

11.3.2 Predict the formation of a precipitate in a double-replacement reaction.

Guide for Reading

Build Vocabulary L2

List the Parts You Know Help students appreciate the meaning of "net ionic equation" by exploring the meaning of phrases such as net income and net worth.

Reading Strategy L2

Anticipation Guide Ask, **In a double-replacement reaction, two ions form a solid precipitate, a molecular compound, or a gas. What happens to the other ions?** *(They remain dissolved in the solution.)* **What would you need to know to predict whether a precipitate forms in a double-replacement reaction?** *(The solubility of all compounds that could form.)*

2 INSTRUCT

Connecting to Your World

Point out that the formation of stalactites and stalagmites is a precipitation reaction. Ask, **How do limestone caverns form?** *(Calcium carbonate reacts with carbon dioxide dissolved in water to form soluble calcium hydrogen carbonate. Carbon dioxide then converts calcium hydrogen carbonate back to calcium carbonate, which precipitates and forms stalactites and stalagmites.)*

Net Ionic Equations

Discuss L2

Ask, **What type of reaction is a precipitation reaction?** *(double-replacement)* **What evidence shows that a double-replacement reaction has occurred?** *(formation of a precipitate, a gas, or a molecular compound)*

11.3 Reactions in Aqueous Solution

Guide for Reading

Key Concepts

- What does a net ionic equation show?
- How can you predict the formation of a precipitate in a double-replacement reaction?

Vocabulary

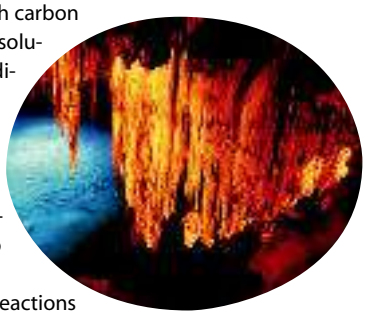
complete ionic equation
spectator ion
net ionic equation

Reading Strategy

Comparing and Contrasting When you compare and contrast things, you examine how they are alike and different. As you read, list the ways that complete ionic equations and net ionic equations are the same and how they are different.

Connecting to Your World

The beauty of a limestone cavern is the result of chemical reactions involving water. Limestone caverns form as calcium carbonate reacts with carbon dioxide dissolved in water and forms soluble calcium hydrogen carbonate. Additional carbon dioxide then converts the calcium hydrogen carbonate back into calcium carbonate. The calcium carbonate precipitates and forms dramatic stalactites and stalagmites. In this section, you will learn to predict the formation of precipitates and write equations to describe the reactions that produce them.



Net Ionic Equations

Your world is water-based. More than 70% of Earth's surface is covered by water, and about 66% of the adult human body is water. It is not surprising, then, that many important chemical reactions take place in water—that is, in aqueous solution.

The reaction of aqueous solutions of silver nitrate with sodium chloride to form solid silver chloride and aqueous sodium nitrate is a double-replacement reaction. The reaction is shown in Figure 11.11.

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

This is the way you have been writing equations involving aqueous solutions of ionic compounds. However, the equation does not show that like most ionic compounds, the reactants and one of the products dissociate, or separate, into cations and anions when they dissolve in water. For example, when sodium chloride dissolves in water, it separates into sodium ions ($Na^+(aq)$) and chloride ions ($Cl^-(aq)$). Similarly, silver nitrate dissociates into silver ions ($Ag^+(aq)$) and nitrate ions ($NO_3^-(aq)$). You can use these ions to write a **complete ionic equation,** an equation that shows dissolved ionic compounds as dissociated free ions.

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

Notice that the nitrate ion and the sodium ion appear unchanged on both sides of the equation. The equation can be simplified by eliminating these ions because they don't participate in the reaction.

$$Ag^+(aq) + \cancel{NO_3^-(aq)} + \cancel{Na^+(aq)} + Cl^-(aq) \longrightarrow AgCl(s) + \cancel{Na^+(aq)} + \cancel{NO_3^-(aq)}$$

Figure 11.11 A precipitate of silver chloride forms when aqueous solutions of silver nitrate and sodium chloride are mixed. **Inferring** ***Which ions do not participate in the reaction?***

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 11.3
- **Core Teaching Resources,** Section 11.3 Review, Interpreting Graphics
- **Laboratory Manual,** Labs 16, 17, 18
- **Small-Scale Chemistry Laboratory Manual,** Lab 16, 17
- **Transparencies,** T121
- **Lab Practical,** 11-2, 11-3, 11-4, 11-5

Technology

- **Interactive Textbook with ChemASAP,** Problem-Solving 11.28, Assessment 11.3

An ion that appears on both sides of an equation and is not directly involved in the reaction is called a **spectator ion.** When you rewrite an equation leaving out the spectator ions, you have the net ionic equation. The **net ionic equation** is an equation for a reaction in solution that shows only those particles that are directly involved in the chemical change.

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

In writing balanced net ionic equations, you must make sure that the ionic charge is balanced. For the previous reaction, the net ionic charge on each side of the equation is zero and is therefore balanced. But consider the skeleton equation for the reaction of lead with silver nitrate.

$$Pb(s) + AgNO_3(aq) \longrightarrow Ag(s) + Pb(NO_3)_2(aq)$$

The nitrate ion is the spectator ion in this reaction. The net ionic equation is this.

$$Pb(s) + Ag^+(aq) \longrightarrow Ag(s) + Pb^{2+}(aq) \text{ (unbalanced)}$$

Why is this equation unbalanced? Notice that a single unit of positive charge is on the reactant side of the equation. Two units of positive charge are on the product side. Placing the coefficient 2 in front of $Ag^+(aq)$ balances the charge. A coefficient of 2 in front of $Ag(s)$ rebalances the atoms.

$$Pb(s) + 2Ag^+(aq) \longrightarrow 2Ag(s) + Pb^{2+}(aq) \text{ (balanced)}$$

A net ionic equation shows only those particles involved in the reaction and is balanced with respect to both mass and charge.

Word Origins

Spectator comes from the Latin verb *spectare*, meaning "to watch." Thus a spectator ion can be thought of as only watching a reaction, not participating. **During a football game, what analogy can you draw to the people in the seats and the football players on the field?**

CONCEPTUAL PROBLEM 11.9

Writing and Balancing Net Ionic Equations

In the photograph, aqueous solutions of iron(III) chloride and potassium hydroxide are mixed. A precipitate of iron(III) hydroxide forms. Identify the spectator ions and write a balanced net ionic equation for the reaction.

1 Analyze ***Identify the relevant concepts.***

Write the complete ionic equation for the reaction, showing any soluble ionic compounds as individual ions. Eliminate aqueous ions that appear as both reactants and products. Balance the net ionic equation.

2 Solve ***Apply concepts to this situation.***

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

The spectator ions are K^+ and Cl^-. The balanced net ionic equation is

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

Practice Problems

28. Write the balanced net ionic equation for this reaction.

$$Ca^{2+}(aq) + OH^-(aq) + H^+(aq) + PO_4^{3-}(aq) \longrightarrow Ca^{2+}(aq) + PO_4^{3-}(aq) + H_2O(l)$$

29. Write the complete ionic equation and net ionic equation for the reaction of aqueous calcium hydroxide with phosphoric acid. The products are calcium phosphate and water.

Interactive Textbook

Problem-Solving 11.28 Solve Problem 28 with the help of an interactive guided tutorial.

with ChemASAP

Differentiated Instruction

Less Proficient Readers L1

Initiate a discussion with students about precipitation reactions that occur in everyday life. Examples include kidney stones, soap scum in bathtubs and showers, and limestone deposits. Explain the value of being able to write net ionic equations as a direct and simple way to describe chemical change. Relate the concept of net ionic equations to net income. Spectator ions can be compared to two people who go to a dance on a double date and then watch while their partners pair up to dance.

CONCEPTUAL PROBLEM 11.9

Answers

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

29. complete ionic equation:

$$3Ca^{2+}(aq) + 6OH^-(aq) + 6H^+(aq) + 2PO_4^{3-}(aq) \rightarrow Ca_3(PO_4)_2(s) + 6H_2O(l)$$

net ionic equation: same as complete ionic equation

Practice Problems Plus L2

Write a balanced net ionic equation for the reaction between sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH). $(H^+(aq) + OH^-(aq) \rightarrow H_2O(l))$

Word Origins L2

The spectators at a football game are present at the game, but they don't participate in it.

Relate L2

If any students have visited underground caves such as Carlsbad Caverns, have them describe what they saw. Explain that the caverns form when carbonic acid dissolves the calcium carbonate (calcite) in limestone. The icicle-like deposits on the roof of the cavern are called **stalactites**. The deposits on the floor are called **stalagmites**. Both form when dissolved calcium carbonate precipitates from groundwater.

Discuss L2

Explain to students that a net ionic equation differentiates between ions that react to form a solid precipitate, a gas, or water, and ions that simply remain in aqueous solution. It is important to note, however, that spectator ions are not completely unaffected by the reaction. They end up paired with different anions or cations than they were paired with when the reaction began.

Answers to...

Figure 11.11 Na^+ and NO_3^-

Predicting the Formation of a Precipitate

Discuss L2

On the board, write the products only of several double-replacement reactions; challenge students to fill in the reactants. Examples include: $\rightarrow AgBr(s) + KNO_3(aq)$, $\rightarrow BaSO_4(s) + 2NaCl(aq)$, and $\rightarrow 2KCl(aq) + CaSO_4(s)$. *($KBr(aq) + AgNO_3(aq)$, $BaCl_2(aq) + Na_2SO_4(aq)$, and $CaCl_2(aq) + K_2SO_4(aq)$)* Remind students that in a double-replacement reaction, the positive ions (cations) of one compound trade places with the positive ions of another compound.

3 ASSESS

Evaluate Understanding L2

To evaluate students' understanding of complete ionic equations, net ionic equations, and the formation of precipitates, write the reactants in some precipitation reactions on the board. Include at least one example for which no reaction occurs. Have students write complete and net ionic equations.

Reteach L1

Review with students the writing and balancing of complete and net ionic equations and the use of solubility rules to predict the outcome of double-replacement reactions. Stress that it is important to note the physical states of reactants and products in precipitation reactions.

Elements Handbook

In the formation of limestone caves, calcium carbonate dissolves in carbonic acid (H_2CO_3). Another reaction occurs when stalagmites form: $Ca^{2+}(aq) + 2HCO_3^-(aq) \rightarrow CaCO_3(s) + CO_2(g) + H_2O(l)$

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 11.3.

with ChemASAP

Table 11.3
Solubility Rules for Ionic Compounds

Compounds	Solubility
Salts of alkali metals and ammonia	Soluble
Nitrate salts and chlorate salts	Soluble
Sulfate salts, except compounds with Pb^{2+}, Ag^+, Hg_2^{2+}, Ba^{2+}, Sr^{2+}, and Ca^{2+}	Soluble
Chloride salts, except compound with Ag^+, Pb^{2+}, and Hg_2^{2+}	Soluble
Carbonates, phosphates, chromates, sulfides, and hydroxides	Most are insoluble

Predicting the Formation of a Precipitate

You have seen that mixing solutions of two ionic compounds can sometimes result in the formation of an insoluble salt called a precipitate. Some combinations of solutions produce precipitates, while others do not. Whether or not a precipitate forms depends upon the solubility of the new compounds that form. **You can predict the formation of a precipitate by using the general rules for solubility of ionic compounds.** These rules are shown in Table 11.3. Will a precipitate form when aqueous solutions of $Na_2CO_3(aq)$ and $Ba(NO_3)_2(aq)$ are mixed?

$$2Na^+(aq) + CO_3^{2-}(aq) + Ba^{2+}(aq) + 2NO_3^-(aq) \longrightarrow ?$$

When these four ions are mixed, the cations could change partners. If they did, the two new compounds that would form are $NaNO_3$ and $BaCO_3$. These are the only new combinations of cation and anion possible. To find out if an exchange will occur, refer to Table 11.3, which gives guidelines for determining whether ion combinations are soluble. Recall that sodium is an alkali metal. Rows 1 and 2 tell you that sodium nitrate will not form a precipitate because alkali metal salts and nitrate salts are soluble. Row 5 indicates that carbonates in general are insoluble. Barium carbonate will precipitate. In this reaction Na^+ and NO_3^- are spectator ions. The net ionic equation for this reaction is as follows.

$$Ba^{2+}(aq) + CO_3^{2-}(aq) \longrightarrow BaCO_3(s)$$

11.3 Section Assessment

30. Key Concept What is a net ionic equation?

31. Key Concept How can you predict the formation of a precipitate in a double-replacement reaction?

32. Write a balanced net ionic equation for each reaction.
- **a.** $Pb(NO_3)_2(aq) + H_2SO_4(aq) \longrightarrow PbSO_4(s) + HNO_3(aq)$
- **b.** $Pb(C_2H_3O_2)_2(aq) + HCl(aq) \longrightarrow PbCl_2(s) + HC_2H_3O_2(aq)$
- **c.** $Na_3PO_4(aq) + FeCl_3(aq) \longrightarrow NaCl(aq) + FePO_4(s)$
- **d.** $(NH_4)_2S(aq) + Co(NO_3)_2(aq) \longrightarrow CoS(s) + NH_4NO_3(aq)$

33. Write a balanced net ionic equation for each reaction. Identify the spectator ions in each reaction.
- **a.** $HCl(aq) + AgNO_3(aq) \longrightarrow$
- **b.** $Pb(C_2H_3O_2)_2(aq) + LiCl(aq) \longrightarrow$
- **c.** $Na_3PO_4(aq) + CrCl_3(aq) \longrightarrow$

34. Identify the precipitate formed when solutions of these ionic compounds are mixed.
- **a.** $H_2SO_4 + BaCl_2 \longrightarrow$
- **b.** $Al_2(SO_4)_3 + NH_4OH \longrightarrow$
- **c.** $AgNO_3 + H_2S \longrightarrow$
- **d.** $CaCl_2 + Pb(NO_3)_2 \longrightarrow$
- **e.** $Ca(NO_3)_2 + Na_2CO_3 \longrightarrow$

35. Will a precipitate form when the following aqueous solutions of ionic compounds are mixed?
- **a.** $AgNO_3$ and Na_2SO_4
- **b.** NH_4Cl and $Ba(NO_3)_2$
- **c.** $CaCl_2$ and K_2SO_4
- **d.** $Pb(NO_3)_2$ and HCl

Elements Handbook

Limestone Caves Refer to page R13 in the Elements Handbook to learn more about the formation of limestone caves. What part does acid (hydrogen ion) play in the dissolving process? What is the reaction that deposits stalactites and stalagmites?

Interactive Textbook

Assessment 11.3 Test yourself on the concepts in Section 11.3.

with ChemASAP

Section 11.3 Assessment

30. A net ionic equation shows only those particles involved in the reaction and is balanced with respect to both mass and charge.

31. Use the general rules for solubility of ionic compounds (Table 11.3).

32. **a.** $Pb^{2+}(aq) + SO_4^{2-}(aq) \rightarrow PbSO_4(s)$
b. $Pb^{2+}(aq) + 2Cl^-(aq) \rightarrow PbCl_2(s)$
c. $Fe^{3+}(aq) + PO_4^{3-}(aq) \rightarrow FePO_4(s)$
d. $Co^{2+}(aq) + S^{2-}(aq) \rightarrow CoS(s)$

33. **a.** $Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$; spectator ions are $H^+(aq)$ and $NO_3^-(aq)$
b. $Pb^{2+}(aq) + 2Cl^-(aq) \rightarrow PbCl_2(s)$; spectator ions are $Li^+(aq)$ and $C_2H_3O_2^-(aq)$
c. $Cr^{3+}(aq) + PO_4^{3-}(aq) \rightarrow CrPO_4(s)$; spectator ions are $Na^+(aq)$ and $Cl^-(aq)$

34. **a.** $BaSO_4(s)$ **b.** $Al(OH)_3(s)$ **c.** $Ag_2S(s)$ **d.** $PbCl_2(s)$ **e.** $CaCO_3(s)$

35. **a.** yes; $Ag_2SO_4(s)$ **b.** no **c.** yes; $CaSO_4(s)$ **d.** yes; $PbCl_2$

Small-Scale LAB

Precipitation Reactions: Formation of Solids

Purpose

To observe, identify, and write balanced equations for precipitation reactions.

Materials

- pencil
- paper
- ruler
- reaction surface
- chemicals shown in the grid below

	$AgNO_3$ (Ag^+)	$Pb(NO_3)_2$ (Pb^{2+})	$CaCl_2$ (Ca^{2+})
Na_2CO_3 (CO_3^{2-})	a	f	k
Na_3PO_4 (PO_4^{3-})	b	g	l
NaOH (OH^-)	c	h	m
Na_2SO_4 (SO_4^{2-})	d	i	n
NaCl (Cl^-)	e	j	o

Procedure

Copy the grid on two sheets of paper. Make each square 2 cm on each side. Draw large black Xs on one of the grids. Place a reaction surface over the grid with black Xs and add the chemicals as shown. Use the other grid as a data table to record your observations for each solution.

Analyze

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

1. Translate the following word equations into balanced chemical equations and explain how the equations represent what happens in grid spaces *a* and *g*.
   - **a.** In grid space *a*, sodium carbonate reacts with silver nitrate to produce sodium nitrate and solid silver carbonate.
   - **b.** In grid space *g*, sodium phosphate reacts with lead(II) nitrate to produce sodium nitrate and solid lead(II) phosphate.
2. Write a word equation to represent what happens in grid space *m*.
3. What happens in grid space *d*? Which other mixings gave similar results? Is it necessary to write an equation when no reaction occurs? Explain.
4. Write balanced equations for the other precipitation reactions you observed.
5. Write balanced net ionic equations for the other precipitation reactions you observed.

You're The Chemist

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

1. **Explain It!** Mix a solution of potassium iodide (KI) with silver nitrate. Then mix potassium iodide solution with lead(II) nitrate. Describe your results. Write balanced equations and net ionic equations for each reaction.
2. **Design It!** Table salt is mostly sodium chloride. Design and carry out an experiment to find out if table salt will form a precipitate with either lead(II) nitrate or silver nitrate. Interpret your results.
3. **Design It!** Design and carry out an experiment to show that iodized table salt contains potassium iodide.

5. $2Ag^+ + CO_3^{2-} \rightarrow Ag_2CO_3(s)$
   $3Ag^+ + PO_4^{3-} \rightarrow Ag_3PO_4(s)$
   $Ag^+ + OH^- \rightarrow AgOH(s)$
   $Ag^+ + Cl^- \rightarrow AgCl(s)$
   $Pb^{2+} + CO_3^{2-} \rightarrow PbCO_3(s)$
   $3Pb^{2+} + 2PO_4^{3-} \rightarrow Pb_3(PO_4)_2(s)$
   $Pb^{2+} + 2OH^- \rightarrow Pb(OH)_2(s)$
   $Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4(s)$
   $Pb^{2+} + 2Cl^- \rightarrow PbCl_2(s)$
   $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(s)$
   $3Ca^{2+} + 2PO_4^{3-} \rightarrow Ca_3(PO_4)_2(s)$
   $Ca^{2+} + 2OH^- \rightarrow Ca(OH)_2(s)$

You're The Chemist

1. $KI + AgNO_3 \rightarrow KNO_3 + AgI(s)$
   $Ag^+ + I^- \rightarrow AgI(s)$
   $2KI + Pb(NO_3)_2 \rightarrow 2KNO_3 + PbI_2(s)$
   $Pb^{2+} + 2I^- \rightarrow PbI_2(s)$
2. Add a drop of $Pb(NO_3)_2$ or $AgNO_3$ to a few grains of salt. Look for white crystals.
3. Place a drop of $Pb(NO_3)_2$ on a small pile of dry table salt. Keep part of the pile dry. Look for yellow lead iodide.

Small-Scale LAB

Precipitation Reactions: Formation of Solids L2

Objective Students observe, identify, and write balanced equations for precipitation reactions.

Prep Time 30 minutes
Class Time 40 minutes

Solution	Preparation
0.05*M* $AgNO_3$	2.1 g in 250 mL
0.2*M* $Pb(NO_3)_2$	16.6 g in 250 mL
0.5*M* $CaCl_2$	13.9 g in 250 mL
1.0*M* Na_2CO_3	26.5 g in 250 mL
0.1*M* Na_3PO_4	9.5 g $Na_3PO_4 \cdot 12H_2O$ in 250 mL
0.5*M* NaOH	20.0 g in 1.0 L
0.2*M* Na_2SO_4	7.1 g in 250 mL
1.0*M* NaCl	14.6 g in 250 mL

Disposal Flush all chemicals down the drain with excess water.

Analyze

1. $Na_2CO_3 + 2AgNO_3 \rightarrow 2NaNO_3 + Ag_2CO_3(s)$
   $2Na_3PO_4 + 3Pb(NO_3)_2 \rightarrow 6NaNO_3 + Pb_3(PO_4)_2(s)$
2. Sodium hydroxide and calcium chloride form sodium chloride and solid calcium hydroxide.
3. Mixings d, n, and o do not react.
4. $Na_3PO_4 + 3AgNO_3 \rightarrow 3NaNO_3 + Ag_3PO_4(s)$
   $NaOH + AgNO_3 \rightarrow NaNO_3 + AgOH(s)$
   (actual products: $NaNO_3 + Ag_2O(s) + H_2O$)
   $NaCl + AgNO_3 \rightarrow NaNO_3 + AgCl(s)$
   $Na_2CO_3 + Pb(NO_3)_2 \rightarrow 2NaNO_3 + PbCO_3(s)$
   $2NaOH + Pb(NO_3)_2 \rightarrow 2NaNO_3 + Pb(OH)_2(s)$
   $Na_2SO_4 + Pb(NO_3)_2 \rightarrow 2NaNO_3 + PbSO_4(s)$
   $2NaCl + Pb(NO_3)_2 \rightarrow 2NaNO_3 + PbCl_2(s)$
   $Na_2CO_3 + CaCl_2 \rightarrow 2NaCl + CaCO_3(s)$
   $2Na_3PO_4 + 3CaCl_2 \rightarrow 6NaCl + Ca_3(PO_4)_2(s)$
   $2NaOH + CaCl_2 \rightarrow 2NaCl + Ca(OH)_2(s)$