CHAPTER 7

Reactions in Aqueous Solutions

INTRODUCTION

Water is a good solvent in the chemical laboratory because many compounds are soluble in water. Many chemical reactions occur in water, and you will study some of them in this chapter. To predict what will happen when two compounds that are dissolved in water are mixed, you will need to learn some rules. These rules will help you predict what kinds of compounds are soluble in water and what kinds of products you can make.

Water is also an important part of our environment, and many common reactions take place in water. For example, the rusting of iron takes place in water. For these reasons, a whole chapter is devoted to what happens when substances are added to water.

There are many different chemical reactions. When you first look at the equation for a reaction, it often looks completely new and unfamiliar. After you learn the material in this chapter, you will be able to classify many of the new reactions you come across into one or more basic categories. Categorizing a reaction is important. By fitting a reaction into a specific familiar category, you automatically know some things about that reaction even if you have never seen that specific reaction before.

CHAPTER DISCUSSION

Precipitation Reactions

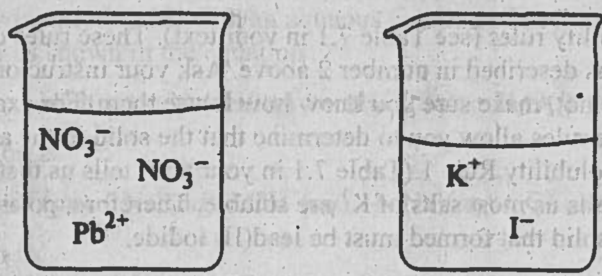
When you mix an aqueous solution of lead(II) nitrate with an aqueous solution of potassium iodide (both solutions are colorless), beautiful yellow crystals are produced in a clear solution. What is the formula for these crystals? What is occurring in this reaction? This type of reaction is called a precipitation reaction, and the solid is termed the precipitate. Let's think about what is going on.

By now, you should be able to write the left side of the chemical equation (the reactant side) from the names given in the above paragraph. Try to do this before reading on.

Since lead(II) has a 2+ charge, and nitrate has a 1− charge, the formula for lead(II) nitrate is $Pb(NO_3)_2$. The potassium ion has a charge of 1+, and the iodide ion has a charge of 1−. So the formula for potassium iodide is KI. Thus the reactant side of the chemical equation is

$$Pb(NO_3)_2(aq) + KI(aq) \rightarrow$$

But what are the products? To understand this, let's think about what the reactants "look like." The reactants are both aqueous solutions of ionic compounds (also known as salts). An aqueous solution of an ionic compound will consist of the ions floating separately in solution. Thus we can visualize the reactants as



When these solutions are mixed together, the four ions

$$Pb^{2+}, NO_3^-, K^+, I^-$$

are all in solution. Therefore there are four possibilities for products. Try to figure the formulas fo these before reading on.

Recall that ions of opposite charges will have attraction for one another and that a molecule will be neutral overall. Therefore we have the following four possibilities for products:

$$Pb(NO_3)_2, KI, PbI_2, KNO_3.$$

We can eliminate the first two possibilities listed above because they are the original reactants. That is, since we know these exist as ions in solution, neither of these two will "reform" simply by mixing with the other solution. Therefore, we know that the possible products are the last two possibilities, and we can write the equation as

$$Pb(NO_3)_2(aq) + KI\ (aq) \rightarrow PbI_2 + KNO_3.$$

As a side note, notice that the subscripts are not necessarily the same on each side. For example, many students make the mistake of writing this equation as (WARNING–THE FOLLOWING CHEMICAL EQUATION IS INCORRECT!)

$$Pb(NO_3)_2(aq) + KI\ (aq) \rightarrow PbI + K(NO_3)_2.$$

Make sure you understand why this is NOT correct. There is no reason that just because a reactant consists of two nitrates (for example) the product must also. This is one reason why it is a good idea to think about the reactants as separate ions when balancing a precipitation reaction.

The correct balanced equation is

$$Pb(NO_3)_2(aq) + 2KI\ (aq) \rightarrow PbI_2 + 2KNO_3$$

This is known as a molecular equation because it shows the complete formulas for all the reactants and products. Note that in this case we have not included phases for the products because we are still not sure which is the solid.

How can we tell which of the two products is the solid? There are a few ways of doing this.

1. We can know something about the possible products. For example, by mixing the solutions a yellow solid was noted. A chemist would know (or could look up) properties of lead(II) iodide and potassium nitrate to see if either was an insoluble yellow solid. In this case, lead(II) iodide is a yellow insoluble solid.

2. We could experiment some more. For example, suppose we mix an aqueous solution of sodium nitrate with an aqueous solution of potassium chloride. In this case, the possible products would be sodium chloride and potassium nitrate (make sure you understand why). However, upon mixing these there is no reaction. Therefore, we know potassium nitrate is not a yellow insoluble solid.

3. We can use the solubility rules (see Table 7.1 in your text). These rules came about by performing similar experiments as described in number 2 above. Ask your instructor if you need to memorize these. Even if you do not, make sure you know how to use them. For example, make sure you understand how these rules allow you to determine that the solid in the above example is lead(II) iodide. In this case, solubility Rule 1 (Table 7.1 in your text) tells us that most nitrate salts are soluble, and Rule 2 tells us most salts of K^+ are soluble. Therefore, potassium nitrate is expected to be soluble, so the solid that formed must be lead(II) iodide.

So, where are we with our equation? We now know the identity of the solid, so we can write

$$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)$$

Again, this is the molecular equation, but in this case we have noted the phase of each reactant and product. However, there are other ways we can represent this equation.

Recall that by writing KI(*aq*), for example, we are stating that the potassium iodide exists in solution as potassium and iodide ions. Thus, we can write the equation as

$$Pb^{2+}(aq) + 2NO_3^-(aq) + 2K^+(aq) + 2I^-(aq) \rightarrow PbI_2(s) + 2K^+(aq) + 2NO_3^-(aq)$$

This more clearly conveys what is occurring in solution. Note that the subscripts that told us how many of a certain ion was present are now coefficients; that is we write

$$2NO_3^-(aq)$$

not

$$(NO_3)_2^-(aq).$$

Also note that the solid is written as a molecule. This is called the complete ionic equation because it contains all the ions that are in solution. This is a rather long way to represent the equation, however, and note that not all of the ions participate. That is, the potassium and nitrate ions do not "do" anything in the reaction (they are termed spectator ions). To simplify this, we can consider only the species that are actually involved in the reaction, and thus we write

$$Pb^{2+}(aq) + 2I^-(aq) \rightarrow PbI_2(s)$$

This is called the net ionic equation. Your text contains many other examples of this in Sections 7.2 and 7.3.

Here are some problems you should be able to answer:

1. Use molecular-level drawings to show what is meant by the terms "strong electrolyte," "insoluble," and "precipitation reaction."
2. If spectator ions do not participate in the reaction, why are they in solution?
3. Mixing an aqueous solution of sodium chloride with an aqueous solution of potassium nitrate is not a chemical reaction. Why not?

Acid–Base Reactions

The acid–base reactions considered in the text are similar to precipitation reactions in that the products can be determined by switching ions. The acid–base reactions are simpler, however, because in all cases that we will consider, one of the products is water.

For example, if we mix hydrochloric acid with an aqueous solution of sodium hydroxide, we get sodium chloride and water as shown in the equation

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

The complete ionic equation is

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

And the net ionic equation is

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

This is the net ionic equation for all acid–base reactions we will consider.

Classifying Chemical Reactions

Sections 7.6-7.7 provide an excellent discussion of classifying chemical reactions. Make sense of Figure 7.12. For example, why are combustion, synthesis, and decomposition reactions all oxidation–reduction reactions? Realize that although there are a seemingly infinite number of actual reactions, there are only a few types of reactions. This is similar to nomenclature; by having a systematic approach to looking at chemical reactions we can know a lot about them without an overabundance of memorization.

LEARNING REVIEW

1. Which one of the following does not tend to drive a reaction to produce products?
   a. formation of a gas
   b. transfer of electrons
   c. color change
   d. formation of water
   e. formation of a solid
2. Write the formulas for the ions that are formed when these ionic compounds are dissolved in water. How many of each kind of ion are produced for each molecule dissolved?
   a. $(NH_4)_2SO_4$
   b. KNO_3
   c. $Na_2Cr_2O_7$
   d. $MgCl_2$
   e. Li_3PO_4
   f. $Al(NO_3)_3$

3. When predicting a product for the reaction between two ionic compounds, we can always eliminate some of the ion pairs as possible products. Give a reason for eliminating each of the pairs as a product of the reaction below.

   $AgNO_3 + Na_3PO_4 \rightarrow$

   a. Ag^+, Na^+

   b. Na^+, NO_3^-

   c. NO_3^-, PO_3^{3-}

4. Use the solubility rules to predict the water solubility of each of the following compounds.

   a. Na_2S

   b. $PbCl_2$

   c. K_2SO_4

   d. $(NH_4)_2CrO_4$

   e. $Pb(OH)_2$

   f. $Ca(NO_3)_2$

   g. $Ba_3(PO_4)_2$

   h. $ZnCl_2$

5. For each word description, write the balanced molecular equation, and identify the product of the reaction.

   a. Aqueous solutions of sodium sulfate and lead(II) nitrate are mixed. One of the products is a white solid.

   b. Aqueous solutions of potassium hydroxide and nickel(II) chloride are mixed. One of the products is a green solid.

   c. Aqueous solutions of potassium sulfide and zinc nitrate are mixed. A pale yellow solid is produced.

   d. Aqueous solutions of silver nitrate and ammonium phosphate are mixed. A white solid is produced.

6. For each of the balanced equations below, write the complete ionic equation.

   a. $3CaCl_2(aq) + 2Na_3PO_4(aq) \rightarrow Ca_3(PO_4)_2(s) + 6NaCl(aq)$

   b. $Cu(NO_3)_2(aq) + K_2S(aq) \rightarrow CuS(s) + 2KNO_3(aq)$

   c. $2AgNO_3(aq) + K_2SO_4(aq) \rightarrow Ag_2SO_4(s) + 2KNO_3(aq)$

7. Complete and balance the equations below and identify the spectator ions.

   a. $Ca(NO_3)_2(aq) + K_2SO_4(aq) \rightarrow$

   b. $(NH_4)_2CO_3(aq) + CuCl_2(aq) \rightarrow$

   c. $NaOH(aq) + Pb(NO_3)_2(aq) \rightarrow$

   d. $Na_2S(aq) + Zn(NO_3)_2(aq) \rightarrow$

   e. $CoCl_2(aq) + Ca(OH)_2(aq) \rightarrow$

8. Write the net ionic equation for each reaction.
   a. $K_2CO_3(aq) + CaCl_2(aq) \rightarrow CaCO_3(s) + 2KCl(aq)$
   b. $Pb(NO_3)_2(aq) + (NH_4)_2S(aq) \rightarrow 2NH_4NO_3(aq) + PbS(s)$
   c. $2LiCl(aq) + 2Hg_2(NO_3)_2(aq) \rightarrow Hg_2Cl_2(s) + 2LiNO_3(aq)$
   d. $2NaOH(aq) + MgCl_2(aq) \rightarrow Mg(OH)_2(s) + 2NaCl(aq)$
9. What salts in aqueous solutions could you mix together to produce the solids below?
   a. $Zn(OH)_2$
   b. $Ba_3(PO_4)_2$
   c. $PbCl_2$
   d. $CaSO_4$
   e. $CoCO_3$
   f. Ag_2SO_4
10. Which of the substances below are strong acids, which are strong bases, and which are neither of these?
    a. HNO_3
    b. $C_2H_4O_2$
    c. H_2SO_4
    d. HCl
    e. $NaCl$
    f. K_2SO_4
11. Write complete ionic equations for the reactions below.
    a. Sodium hydroxide reacts with sulfuric acid.
    b. Hydrochloric acid reacts with potassium hydroxide.
    c. Nitric acid reacts with sodium hydroxide.
12. Write net ionic equations for each reaction in Problem 11.
13. Which of the reactions below are acid/base reactions?
    a. $K_2SO_4(aq) + Pb(NO_3)(aq) \rightarrow PbSO_4(s) + 2KNO_3(aq)$
    b. $KOH(aq) + HNO_3(aq) \rightarrow KNO_3(aq) + H_2O(l)$
    c. $H_2SO_4(aq) + 2NaOH(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(l)$
    d. $Na_2CO_3(aq) + CoCl_2(aq) \rightarrow CoCO_3(s) + 2NaCl(aq)$

14. How many electrons do the elements below either gain or lose? For example, potassium atoms lose one electron.

$$K \rightarrow K^+ + e^-$$

a. Br_2

b. Mg

c. H_2

d. Al

e. O_2

f. S

15. Show how the ions below can gain or lose electrons to form atoms or molecules. For example, a sodium ion gains one electron to form an atom of sodium.

$$Na^+ + e^- \rightarrow Na$$

a. $2Cl^-$

b. K^+

c. $\cancel{4P^{3+}}$ $4P^{3-}$

d. Ca^{2+}

e. $2I^-$

f. Al^{3+}

16. For each reaction below, write equations showing the gain and loss of electrons.

a. $Cu(s) + 2AgNO_3(aq) \rightarrow 2Ag(s) + Cu(NO_3)_2(aq)$

b. $2HCl(aq) + Zn(s) \rightarrow H_2(g) + ZnCl_2(aq)$

c. $2NaBr(aq) + Cl_2(g) \rightarrow 2NaCl(aq) + Br_2(g)$

d. $2Hg(l) + O_2(g) \rightarrow 2HgO(s)$

17. Classify the reactions below as a precipitation reaction, an acid–base reaction, or an oxidation–reduction reaction.

a. $2NaCl(s) + Br_2(l) \rightarrow 2NaBr(s) + Cl_2(g)$

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

c. $2NaOH(aq) + H_2SO_4(aq) \rightarrow 2H_2O(l) + Na_2SO_4(aq)$

d. $2AgNO_3(aq) + Fe(s) \rightarrow Fe(NO_3)_2(aq) + 2Ag(s)$

e. $2KOH(aq) + ZnCl_2(aq) \rightarrow Zn(OH)_2(s) + 2KCl(aq)$

18. Classify the reactions below as combustion, synthesis or decomposition reactions.

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

b. $C_7H_{16}(g) + 11O_2(g) \rightarrow 7CO_2(g) + 8H_2O(g)$

c. $16Cu(s) + S_8(s) \rightarrow 8Cu_2S(s)$

d. $2NaNO_3(s) \rightarrow 2NaNO_2(s) + O_2(g)$

e. $SO_3(g) + H_2O(l) \rightarrow H_2SO_4(l)$

19. Write balanced equations for each of the word descriptions. Classify each reaction as precipitation, oxidation–reduction, or acid–base.
    a. Ethyl alcohol, a gasoline additive, burns in the presence of oxygen gas to produce carbon dioxide and water vapor.
    b. Aqueous solutions of ammonium sulfide and lead nitrate are mixed to produce solid lead sulfide and aqueous ammonium nitrate.
    c. Aluminum metal reacts with oxygen to produce solid aluminum oxide.
    d. Sodium metal reacts with liquid water to produce aqueous sodium hydroxide and hydrogen gas.
    e. Aqueous solutions of potassium hydroxide and nitric acid are mixed to produce aqueous potassium nitrate and liquid water.
    f. Aqueous solutions of sodium phosphate and aqueous silver nitrate are mixed to produce solid silver phosphate and aqueous sodium nitrate.

ANSWERS TO LEARNING REVIEW

1. Only "c," color change, does not tend to make a reaction occur.
2.
    a. $2NH_4^+$ $1SO_4^{2-}$
    b. $1K^+$ $1NO_3^-$
    c. $2Na^+$ $1Cr_2O_7^{2-}$
    d. $1Mg^{2+}$ $2Cl^-$
    e. $3Li^+$ $1PO_4^{3-}$
    f. $1Al^{3+}$ $3NO_3^-$
3.
    a. Both Ag^+ and Na^+ are cations. An anion and a cation are needed to form a neutral product.
    b. $NaNO_3$ is soluble in water, and so it exists in solution as Na^+ ions and NO_3^- ions.
    c. Both NO_3^- and PO_4^{3-} are anions. An anion and a cation are needed to form a neutral product.
4.
    a. water soluble (Rule 2)
    b. not soluble (Rule 3)
    c. water soluble (Rule 2)
    d. water soluble (Rule 2)
    e. not soluble (Rule 5)
    f. water soluble (Rule 1)
    g. not soluble (Rule 6)
    h. water soluble (Rule 3)

5.

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

The product is lead(II) sulfate.

b. $NiCl_2(aq) + 2KOH(aq) \rightarrow Ni(OH)_2(s) + 2KCl(aq)$

The product is nickel(II) hydroxide.

c. $K_2S(aq) + Zn(NO_3)_2(aq) \rightarrow ZnS(s) + 2KNO_3(aq)$

The product is zinc sulfide.

d. $3AgNO_3(aq) + (NH_4)_3PO_4(aq) \rightarrow Ag_3PO_4(s) + 3NH_4NO_3(aq)$

The product is silver phosphate.

6.

a. $3Ca^{2+} + 6Cl^- + 6Na^+ + 2PO_4^{3-} \rightarrow Ca_3(PO_4)_2(s) + 6Na^+ + 6Cl^-$

b. $Cu^{2+} + 2NO_3^- + 2K^+ + S^{2-} \rightarrow CuS(s) + 2K^+ + 2NO_3^-$

c. $2Ag^+ + 2NO_3^- + 2K^+ + SO_4^{2-} \rightarrow Ag_2SO_4(s) + 2K^+ + 2NO_3^-$

7.

a. $Ca(NO_3)_2(aq) + K_2SO_4(aq) \rightarrow CaSO_4(s) + 2KNO_3(aq)$

K^+ and NO_3^- are the spectator ions.

b. $(NH_4)_2CO_3(aq) + CuCl_2(aq) \rightarrow CuCO_3(s) + 2NH_4Cl(aq)$

NH_4^+ and Cl^- are the spectator ions.

c. $2NaOH(aq) + Pb(NO_3)_2(aq) \rightarrow Pb(OH)_2(s) + 2NaNO_3(aq)$

Na^+ and NO_3^- are the spectator ions.

d. $Na_2S(aq) + Zn(NO_3)_2(aq) \rightarrow ZnS(s) + 2NaNO_3(aq)$

Na^+ and NO_3^- are the spectator ions.

e. $CoCl_2(aq) + Ca(OH)_2(aq) \rightarrow Co(OH)_2(s) + CaCl_2(aq)$

Ca^{2+} and Cl^- are the spectator ions.

8.

a. $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(s)$

b. $Pb^{2+} + S^{2-} \rightarrow PbS(s)$

c. $Hg_2^{2+} + 2Cl^- \rightarrow Hg_2Cl_2(s)$

d. $Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2(s)$

9. It is possible to produce the solids below from several different soluble salts, so your answer could be correct and not the same as the answer below. If your answer does not match the one below, use the solubility rules to help you determine whether the aqueous salt solutions you chose would be soluble in water and whether an exchange of anions would produce the desired insoluble salt.

a. $Zn(NO_3)_2$ and NaOH

b. $Ba(NO_3)_2$ and K_3PO_4

c. $Pb(NO_3)_2$ and NaCl

d. $CaCl_2$ and $(NH_4)_2SO_4$

e. $Co(NO_3)_2$ and Na_2CO_3

f. $AgNO_3$ and K_2SO_4

10.

a. HNO_3 is a strong acid.

b. $C_2H_4O_2$ is a weak acid, so the correct answer is neither of these.

c. H_2SO_4 is a strong acid.

d. HCl is a strong acid.

e. NaCl is a salt produced when HCl and NaOH react, so it is neither a strong acid nor a strong base.

f. K_2SO_4 is a salt produced when H_2SO_4 and KOH react, so it is neither a strong acid nor a strong base.

11.

a. $2Na^+ + 2OH^- + 2H^+ + SO_4^{2-} \rightarrow 2Na^+ + SO_4^{2-} + 2H_2O(l)$

b. $K^+ + OH^- + H^+ + Cl^- \rightarrow K^+ + Cl^- + H_2O(l)$

c. $Na^+ + OH^- + H^+ + NO_3^- \rightarrow Na^+ + NO_3^- + H_2O(l)$

12.

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

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

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

13.

a. This is a precipitation reaction.

b. This is an acid–base reaction. The products are water and the salt KNO_3.

c. This is an acid–base reaction. The products are water and the salt Na_2SO_4.

d. This is a precipitation reaction.

14. When atoms or molecules lose electrons, a positively charged cation is produced. When electrons are gained, then a negatively charged anion is produced. You can show how electrons are gained or lost by adding electrons to either the right side or the left side of an equation.

a. $Br_2 + 2e^- \rightarrow 2Br^-$

b. $Mg \rightarrow Mg^{2+} + 2e^-$

c. $H_2 \rightarrow 2H^+ + 2e^-$

d. $Al \rightarrow Al^{3+} + 3e^-$

e. $O_2 + 4e^- \rightarrow 2O^{2-}$

f. $S + 2e^- \rightarrow S^{2-}$

15. Ions can either gain or lose electrons to become neutral atoms or molecules. You can show whether the ions must lose or gain electrons by adding electrons to either the right side or the left side of an equation.

a. $2Cl^- \rightarrow Cl_2 + 2e^-$

b. $K^+ + e^- \rightarrow K$

c. $4P^{3-} \rightarrow P_4 + 12e^-$

d. $Ca^{2+} + 2e^- \rightarrow Ca$

e. $2I^- \rightarrow I_2 + 2e^-$

f. $Al^{3+} + 3e^- \rightarrow Al$

16. When presented with a reaction where electrons are transferred, it is possible to extract the parts of the reaction where electrons are lost and where electrons are gained and to write each part separately. Notice that the number of electrons lost is equal to the number gained.

a. $Cu \rightarrow Cu^{2+} + 2e^-$ Two electrons are lost
$2Ag^+ + 2e^- \rightarrow 2Ag$ Two electrons are gained

b. $Zn \rightarrow Zn^{2+} + 2e^-$ Two electrons are lost
$2H^+ + 2e^- \rightarrow H_2$ Two electrons are gained

c. $2Br^- \rightarrow Br_2 + 2e^-$ Two electrons are lost
$Cl_2 + 2e^- \rightarrow H_2$ Two electrons are gained

d. $2Hg \rightarrow 2Hg^{2+} + 4e^-$ Four electrons are lost
$O_2 + 4e^- \rightarrow 2O^{2-}$ Four electrons are gained

17.

a. In this reaction, two chloride ions lose electrons to become a chlorine molecule, and a bromine molecule gains two electrons to become two bromide ions. This is an oxidation–reduction reaction. Because the chloride ion paired with sodium is exchanged for a bromide ion, this kind of reaction is often called a replacement reaction.

b. Two aqueous solutions containing ionic compounds react, and one of the products is the ionic solid $PbSO_4$. This is a precipitation reaction.

c. The base NaOH reacts with the acid H_2SO_4 to produce water. This is an acid–base reaction.

d. In this reaction, two Ag^+ ions gain two electrons to become two atoms of silver, and an atom of iron loses two electrons to become an Fe^{2+} ion. This is an oxidation–reduction reaction. Because the silver ion paired with the nitrate ion is exchanged for an iron ion, this kind of reaction is called a replacement reaction.

e. Two aqueous solutions containing ionic compounds react and one of the products is the ionic solid $Zn(OH)_2$. This is an example of a precipitation reaction.

18.

a. Molecular nitrogen and molecular hydrogen react to produce a larger molecule, ammonia. This is a synthesis reaction.

b. A molecule that is composed of carbon and hydrogen reacts with oxygen gas. The products are carbon dioxide and water. Reactions that have oxygen as a reactant are members of a sub-class of oxidation–reduction reactions called combustion reactions.

c. Elemental copper reacts with elemental sulfur. A compound containing both elements is the product. This is a synthesis reaction.

d. Solid sodium nitrate is converted to two simpler molecules, sodium nitrite and molecular oxygen. This is an example of a decomposition reaction.

e. In this reaction, two small molecules combine to produce one larger molecule. This is an example of a synthesis reaction.

19.

a. $C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$

A molecule reacts with oxygen gas. Because this reaction has oxygen as a reactant, it is an oxidation–reduction reaction.

b. $(NH_4)_2S(aq) + Pb(NO_3)_2(aq) \rightarrow PbS(s) + 2NH_4NO_3(aq)$

Two aqueous solutions are mixed to produce a solid product (precipitation reaction).

c. $4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$

Elemental aluminum loses three electrons to become Al^{3+}, and molecular oxygen gains two electrons to become O^{2-}. This is an oxidation–reduction reaction.

d. $2Na(s) + 2H_2O(l) \rightarrow 2NaOH(aq) + H_2(g)$

Sodium metal loses an electron to become Na^+, and two hydrogen ions gain an electron to become hydrogen gas. This is an oxidation–reduction reaction.

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

Aqueous solutions of the base KOH and the acid HNO_3 are mixed to produce liquid water, so this is an acid–base reaction.

f. $Na_3PO_4(aq) + 3AgNO_3(aq) \rightarrow Ag_3PO_4(s) + 3NaNO_3(aq)$

Two aqueous solutions are mixed. The product is a solid, Ag_3PO_4, so this is a precipitation reaction.