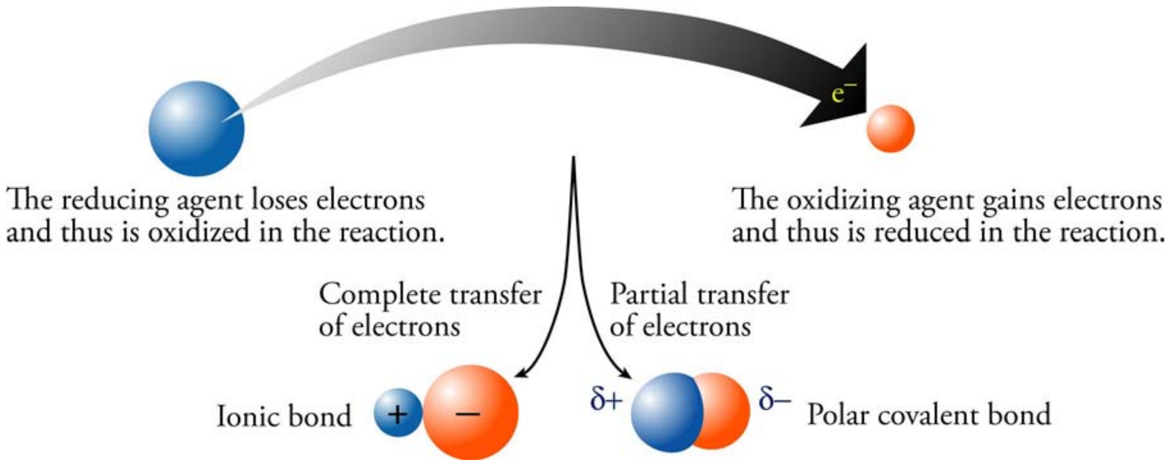
Chapter 6
Oxidation-Reduction Reactions



Section Goals and Introductions

Section 6.1 An Introduction to Oxidation-Reduction Reactions

Goals

- *To describe what oxidation and reduction mean to the chemist.*
- *To describe chemical reactions for which electrons are transferred (oxidation-reduction reactions).*
- *To describe oxidizing agents and reducing agents.*

In many chemical reactions, electrons are completely or partially transferred from one atom to another. These reactions are called oxidation-reduction reactions (or redox reactions). This section provides examples of these reactions and introduces the terms oxidation, reduction, oxidizing agent, and reducing agent, which are summarized in Figure 6.2.

Section 6.2 Oxidation Numbers

Goal: To describe what oxidation numbers are, how they can be determined, and how they can be used to determine (1) whether the reaction is an oxidation-reduction reaction, (2) what is oxidized in an oxidation-reduction reaction, (3) what is reduced in an oxidation-reduction reaction, (4) what the oxidizing agent is in an oxidation-reduction reaction, and (5) what the reducing agent is in an oxidation-reduction reaction.

Oxidation numbers, which are described in this section, provide a tool that allows you to determine the things mentioned in the goal above. *Sample Study Sheet 6.1: Assignment of Oxidation Numbers* and Tables 6.1 and 6.2, which support the study sheet, summarize the process. The section on our Web site called *Balancing Equations for Redox Reaction* describes how you can use oxidation numbers.

Internet: Balancing Redox Reactions

Section 6.3 Types of Chemical Reactions

Goal: To describe different types of chemical reactions.

Chemical reactions can be classified into types of similar reactions. This section describes some of these types: combination, decomposition, combustion, and single-displacement reactions. You will learn how to identify each type of reaction from chemical equations. The section also describes how you can write chemical equations for combustion reactions (*Study Sheet 6.2*). The attempt to help you visualize chemical changes on the particle level continues with a description of the single-displacement reaction between solid zinc and aqueous copper(II) sulfate (Figure 6.4). The animation on our Web site called *Single-Displacement Reactions* will help you visualize single-displacement reactions.

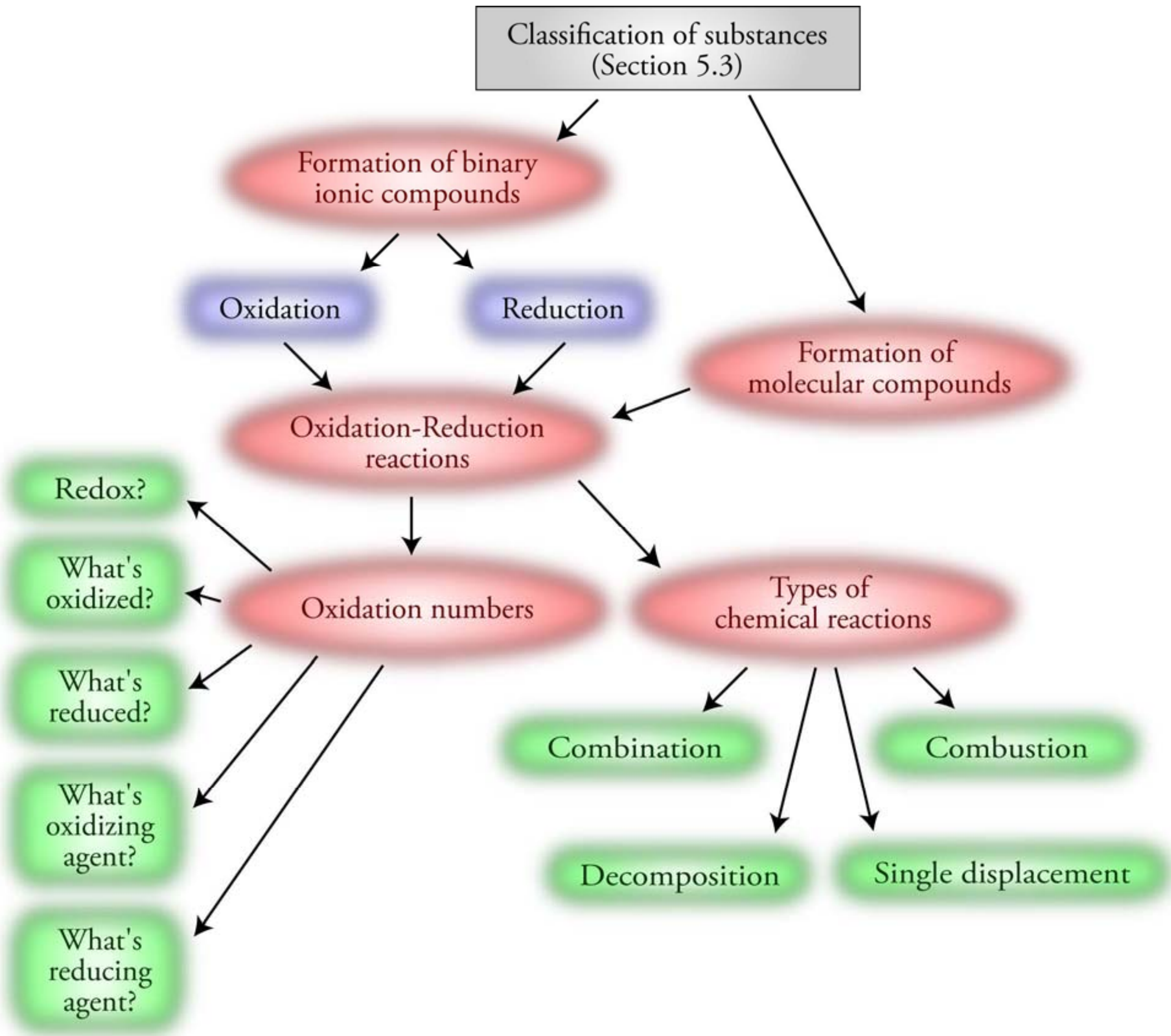
Internet: Single-Displacement Reaction

Section 6.4 Voltaic Cells

Goal: To show how oxidation-reduction reactions can be used to create voltaic cells—that is, batteries.

This is one of the sections that are spread throughout the text that show you how what you are learning relates to the real world. In this case, you see how electrons transferred in oxidation-reduction reactions can be made to pass through a wire that separates the reactants, thus creating a voltaic cell, which is often called a battery. This section describes the fundamental components of voltaic cells and describes several different types.

Chapter 6 Map



Chapter Checklist

- ☐ Read the Review Skills section. If there is any skill mentioned that you have not yet mastered, review the material on that topic before reading this chapter.
- ☐ Read the chapter quickly before the lecture that describes it.
- ☐ Attend class meetings, take notes, and participate in class discussions.
- ☐ Work the Chapter Exercises, perhaps using the Chapter Examples as guides.
- ☐ Study the Chapter Glossary and test yourself on our Web site:

  Internet: Glossary Quiz
- ☐ Study all of the Chapter Objectives. You might want to write a description of how you will meet each objective. (Although it is best to master all of the objectives, the following objectives are especially important because they pertain to skills that you will need while studying other chapters of this text: 7 and 8.)
- ☐ Reread the Study Sheets in this chapter and decide whether you will use them or some variation on them to complete the tasks they describe.

  Sample Study Sheet 6.1: Assignment of Oxidation Numbers

  Sample Study Sheet 6.2: Writing Equations for Combustion Reactions
- ☐ Memorize the guidelines in Table 6.2 for assigning oxidation numbers.
- ☐ To get a review of the most important topics in the chapter, fill in the blanks in the Key Ideas section.
- ☐ Work all of the selected problems at the end of the chapter, and check your answers with the solutions provided in this chapter of the study guide.
- ☐ Ask for help if you need it.

Web Resources

Internet: Balancing Equations for Redox Reactions

Internet: Single-Displacement Reaction

Internet: Glossary Quiz

Exercises Key

Exercise 6.1 - Oxidation Numbers: In one part of the steel manufacturing process, carbon is combined with iron to form pig iron. Pig iron is easier to work with than pure iron because it has a lower melting point (about 1130 °C, compared to 1539 °C for pure iron) and is more pliable. The following equations describe its formation. Determine the oxidation number for each atom in the formulas. Decide whether each reaction is a redox reaction, and if it is, identify what is oxidized, what is reduced, what the oxidizing agent is, and what the reducing agent is. (Obj 3)

$$2C(s) + O_2(g) \rightarrow 2CO(g)$$

$$Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(l) + 3CO_2(g)$$

$$2CO(g) \rightarrow C(\text{in iron}) + CO_2(g)$$

Solution:

Atoms in pure elements have an oxidation number of zero, so the C atoms in C(s) and C(in iron), the O atoms in O_2, and the Fe atoms in Fe(s) have an oxidation number of zero.

Oxygen atoms combined with other elements in compounds have an oxidation number of –2 (except in peroxides), so each O atom in CO, Fe_2O_3, and CO_2 has an oxidation number of –2.

Each Fe ion in Fe_2O_3 has a +3 charge, so each has an oxidation number of +3.

Because the sum of the oxidation number of the atoms in an uncharged molecule is zero, each C atom in CO must have an oxidation number of +2, and each C atom in CO_2 must have an oxidation number of +4.

The oxidation numbers for each atom are above their symbols in the equations below.

$$2\overset{0}{C}(s) + \overset{0}{O}_2(g) \rightarrow 2\overset{+2}{C}\overset{-2}{O}(g)$$

$$\overset{+3}{Fe}_2\overset{-2}{O}_3(s) + \overset{+2}{C}\overset{-2}{O}(g) \rightarrow 2\overset{0}{Fe}(l) + 3\overset{+4}{C}\overset{-2}{O}_2(g)$$

$$2\overset{+2}{C}\overset{-2}{O}(g) \rightarrow \overset{0}{C}(\text{in iron}) + \overset{+4}{C}\overset{-2}{O}_2(g)$$

They are all redox reactions.

In the first reaction, each carbon atom increases its oxidation number from 0 to +2, so **C(s) is oxidized and is the reducing agent**. *Each oxygen atom decreases its oxidation number from 0 to –2, so* **O_2 is reduced and is the oxidizing agent**.

In the second reaction, each carbon atom increases its oxidation number from +2 to +4, so **each carbon atom in CO(g) is oxidized,** *and* **CO(g) is the reducing agent**. *Each iron atom in Fe_2O_3 decreases its oxidation number from +3 to 0, so* **each Fe atom in Fe_2O_3 is reduced,** *and* **Fe_2O_3 is the oxidizing agent**.

Because there is only one reactant in the third reaction, it is different from the other two. Some of the carbon atoms in CO(g) are oxidized from +2 to +4, and some of them are reduced from +2 to 0. Thus **carbon atoms in CO are both oxidized and reduced**, and **CO is both the oxidizing agent and the reducing agent**.

Exercise 6.2 - Combustion Reactions: Write balanced equations for the complete combustion of (a) $C_4H_{10}(g)$, (b) $C_3H_7OH(l)$, and (c) $C_4H_9SH(l)$. *(Obj 8)*

Solution:

a. $\mathbf{2C_4H_{10}(g) + 13O_2(g) \rightarrow 8CO_2(g) + 10H_2O(l)}$

b. $\mathbf{2C_3H_7OH(l) + 9O_2(g) \rightarrow 6CO_2(g) + 8H_2O(l)}$

c. $\mathbf{2C_4H_9SH(l) + 15O_2(g) \rightarrow 8CO_2(g) + 10H_2O(l) + 2SO_2(g)}$

Exercise 6.3 - Classification of Chemical Reactions: Classify each of these reactions as a combination reaction, a decomposition reaction, a combustion reaction, or a single-displacement reaction. *(Obj 7)*

a. $2HgO(s) \xrightarrow{\Delta} 2Hg(l) + O_2(g)$ **decomposition**

b. $C_{12}H_{22}O_{11}(s) + 12O_2(g) \rightarrow 12CO_2(g) + 11H_2O(l)$ **combustion**

c. $B_2O_3(s) + 3Mg(s) \xrightarrow{\Delta} 2B(s) + 3MgO(s)$ **single-displacement**

d. $C_2H_4(g) + H_2(g) \rightarrow C_2H_6(g)$ **combination**

Review Questions Key

1. For each of the following ionic formulas, write the formula for the cation and the formula for the anion.
   a. $FeBr_3$ **Fe^{3+} and Br^-**
   b. $Co_3(PO_4)_2$ **Co^{2+} and PO_4^{3-}**
   c. AgCl **Ag^+ and Cl^-**
   d. $(NH_4)_2SO_4$ **NH_4^+ and SO_4^{2-}**

2. Classify each of the following formulas as representing a binary ionic compound, an ionic compound with polyatomic ions, or a molecular compound.
   a. CF_4 **molecular**
   b. $Pb(C_2H_3O_2)_2$ **ionic with polyatomic ion**
   c. $CoCl_2$ **binary ionic**
   d. C_2H_5OH **molecular**
   e. H_2S **molecular**
   f. ClF **molecular**
   g. $Cr(OH)_3$ **ionic with polyatomic ion**
   h. H_3PO_4 **molecular**

3. Balance the following equations. (C_8H_{18} is a component of gasoline, and P_2S_5 is used to make the insecticides parathion and malathion.)
   a. $C_8H_{18}(l) + \mathbf{25/2}O_2(g) \rightarrow \mathbf{8}CO_2(g) + \mathbf{9}H_2O(l)$

      or $\mathbf{2}C_8H_{18}(l) + \mathbf{25}O_2(g) \rightarrow \mathbf{16}CO_2(g) + \mathbf{18}H_2O(l)$

   b. $\mathbf{4}P_4(s) + \mathbf{5}S_8(s) \rightarrow \mathbf{8}P_2S_5(s)$

Key Ideas Answers

4. According to the modern convention, any chemical change in which an element **loses** electrons is called an oxidation.
6. Electrons are **rarely** found unattached to atoms. Thus, for one element or compound to lose electrons and be **oxidized**, another element or compound must be there to gain the electrons and be **reduced**. In other words, **oxidation** (loss of electrons) must be accompanied by **reduction** (gain of electrons).
8. The separate oxidation and reduction equations are called **half-reactions**.
10. A(n) **oxidizing agent** is a substance that gains electrons, making it possible for another substance to lose electrons and be oxidized.
12. Just think of oxidation numbers as tools for keeping track of the **flow of electrons** in redox reactions.
14. In combination reactions, **two or more** elements or compounds combine to form one compound.
16. In a combustion reaction, oxidation is very rapid and is accompanied by **heat** and usually **light**.
18. When a substance that contains hydrogen is burned completely, the hydrogen forms **water**.
20. In single-displacement reactions, atoms of one element in a compound are displaced (or replaced) by atoms from a(n) **pure element**.
21. Strictly speaking, a battery is a series of **voltaic cells** joined in such a way that they work together. A battery can also be described as a device that converts **chemical energy** into **electrical energy** using redox reactions.
23. Metal strips in voltaic cells are called electrodes, which is the general name for **electrical conductors** placed in half-cells of voltaic cells.
25. The cathode is the electrode in a voltaic cell at which **reduction** occurs. By convention, the cathode is designated the **positive electrode**. Because electrons flow along the wire to the cathode, and because substances gain those electrons to become more negative (or less positive), the cathode surroundings tend to become more negative. Thus cations are attracted to the cathode.
27. Voltage, a measure of the strength of an electric current, represents the **force** that moves electrons from the anode to the cathode in a voltaic cell. When a greater voltage is applied in the opposite direction, electrons can be pushed from what would normally be the cathode toward the voltaic cell’s anode. This process is called **electrolysis**.

Problems Key

Section 6.1 An Introduction to Oxidation-Reduction Reactions

30. Are the electrons in the following redox reactions transferred completely from the atoms of one element to the atoms of another, or are they only partially transferred?

    a. $4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$ **complete – ionic bonds formed**

    b. $C(s) + O_2(g) \rightarrow CO_2(g)$ **incomplete – polar covalent bonds formed**

32. Are the electrons in the following redox reactions transferred completely from the atoms of one element to the atoms of another, or are they only partially transferred?

    a. $S_8(s) + 8O_2(g) \rightarrow 8SO_2(g)$ **incomplete – polar covalent bonds formed**

    b. $P_4(s) + 6Cl_2(g) \rightarrow 4PCl_3(l)$ **incomplete – polar covalent bonds formed**

34. Aluminum bromide, $AlBr_3$, which is used to add bromine atoms to organic compounds, can be made by passing gaseous bromine over hot aluminum. Which of the following half-reactions for this oxidation-reduction reaction describes the oxidation, and which one describes the reduction?

    $2Al \rightarrow 2Al^{3+} + 6e^-$ **oxidation** – *loss of electrons*

    $3Br_2 + 6e^- \rightarrow 6Br^-$ **reduction** – *gain of electrons*

Section 6.2 Oxidation Numbers

36. Determine the oxidation number for the atoms of each element in the following formulas. *(Obj 3)*

    a. S_8 *Because this is a pure, uncharged element, each* **S** *is* **zero**.

    b. S^{2-} *Because this is a monatomic ion, the* **S** *is* **–2**.

    c. Na_2S *This is a binary ionic compound. The oxidation numbers are equal to the charges. Each* **Na** *is* **+1**, *and the* **S** *is* **–2**.

    d. FeS *This is a binary ionic compound. The oxidation numbers are equal to the charges. The* **Fe** *is* **+2**, *and the* **S** *is* **–2**.

38. Determine the oxidation number for the atoms of each element in the following formulas. *(Obj 3)*

    a. Sc_2O_3 *This is a binary ionic compound. The oxidation numbers are equal to the charges. Each* **Sc** *is* **+3**, *and each* **O** *is* **–2**.

    b. RbH *This is a binary ionic compound. The oxidation numbers are equal to the charges. The* **Rb** *is* **+1**, *and the* **H** *is* **–1**.

    c. N_2 *Because this is a pure, uncharged element, the oxidation number for each* **N** *is* **zero**.

    d. NH_3 *This is a molecular compound.* **H** *is* **+1** *in molecular compounds.* **N** *must be* **–3** *for the sum to be zero.*

40. Determine the oxidation number for the atoms of each element in the following formulas. *(Obj 3)*

   a. ClF_3 *This is a molecular compound.* **F** *is* **–1** *when combined with other elements.* **Cl** *must be* **+3** *for the sum to be zero.*

   b. H_2O_2 *This is a molecular compound.* **H** *is* **+1** *in molecular compounds.* **O** *is* **–1** *in peroxides.*

   c. H_2SO_4 **H** *is* **+1** *in molecular compounds.* **O** *is* **–2** *in molecular compounds other than peroxides.* **S** *must be* **+6** *for the sum to be 0.*

42. Determine the oxidation number for the atoms of each element in the following formulas. *(Obj 3)*

   a. HPO_4^{2-} *This is a polyatomic ion.* **H** *is* **+1** *in polyatomic ions.* **O** *is* **–2** *in polyatomic ions other than peroxide.* **P** *must be* **+5** *for the sum to be –2.*

   b. $NiSO_4$ *This is an ionic compound with a polyatomic ion. The* **Ni** *is in the form of the monatomic ion Ni^{2+}, so it has an oxidation number of* **+2. O** *is* **–2** *when combined with other elements, except in peroxides.* **S** *must be* **+6** *for the sum to be zero.*

   c. $N_2O_4^{2-}$ *This is a polyatomic ion.* **O** *is* **–2** *when combined with other elements, except in peroxides.* **N** *must be* **+3** *for the sum to be –2.*

   d. $Mn_3(PO_4)_2$ *This is an ionic compound with a polyatomic ion. The* **Mn** *is in the form of the monatomic ion Mn^{2+}, so it has an oxidation number of* **+2**. **O** *is* **–2** *when combined with other elements, except in peroxides. Each* **P** *must be* **+5** *for the sum to be zero.*

45. About 47% of the hydrochloric acid produced in the United States is used for cleaning metallic surfaces. Hydrogen chloride, HCl, which is dissolved in water to make the acid, is formed in the reaction of chlorine gas and hydrogen gas, displayed below. Determine the oxidation number for each atom in the equation, and decide whether the reaction is a redox reaction or not. If it is redox, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent. *(Objs 3–6)*

$$\overset{0}{Cl_2}(g) + \overset{0}{H_2}(g) \rightarrow 2\overset{+1}{H}\overset{-1}{Cl}(g)$$

Yes, it's redox.

H atoms in H_2 are oxidized, Cl atoms in Cl_2 are reduced, Cl_2 is the oxidizing agent, and H_2 is the reducing agent.

47. Water and carbon dioxide fire extinguishers should not be used on magnesium fires because both substances react with magnesium and generate enough heat to intensify the fire. Determine the oxidation number for each atom in the equations that describe these reactions (displayed below), and decide whether each reaction is a redox reaction or not. If it is redox, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent. *(Objs 3-6)*

$$\overset{0}{Mg}(s) + 2\overset{+1}{H_2}\overset{-2}{O}(l) \rightarrow \overset{+2}{Mg}(\overset{-2}{O}\overset{+1}{H})_2(aq) + \overset{0}{H_2}(g) + \text{heat}$$

Yes, it's redox.

Mg atoms in Mg(s) are oxidized, H atoms in H_2O are reduced, H_2O is the oxidizing agent, and Mg is the reducing agent.

$$2\overset{0}{Mg}(s) + \overset{+4}{C}\overset{-2}{O_2}(g) \rightarrow 2\overset{+2}{Mg}\overset{-2}{O}(s) + \overset{0}{C}(s) + \text{heat}$$

Yes, it's redox.

Mg atoms in Mg(s) are oxidized, C atoms in CO_2 are reduced, CO_2 is the oxidizing agent, and Mg is the reducing agent.

49. Formaldehyde, CH_2O, which is used in embalming fluids, is made from methanol in the reaction described below. Determine the oxidation number for each atom in this equation, and decide whether the reaction is a redox reaction or not. If it is redox, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent. *(Objs 3-6)*

$$2\overset{-2}{C}\overset{+1}{H_3}\overset{-2}{O}\overset{+1}{H} + \overset{0}{O_2} \rightarrow 2\overset{0}{C}\overset{+1}{H_2}\overset{-2}{O} + 2\overset{+1}{H_2}\overset{-2}{O}$$

Yes, it's redox.

C atoms in CH_3OH are oxidized, O atoms in O_2 are reduced, O_2 is the oxidizing agent, and CH_3OH is the reducing agent.

51. For each of the following equations, determine the oxidation number for each atom in the equation, and indicate whether the reaction is a redox reaction. If the reaction is redox, identify what is oxidized, what is reduced, the oxidizing agent, and the reducing agent. *(Objs 3-6)*

a. $\overset{0}{Co}(s) + 2\overset{+1}{Ag}\overset{+5}{N}\overset{-2}{O_3}(aq) \rightarrow \overset{+2}{Co}(\overset{+5}{N}\overset{-2}{O_3})_2(aq) + 2\overset{0}{Ag}(s)$

Co in Co(s) is oxidized, and Co(s) is the reducing agent. Ag in $AgNO_3$ is reduced, and $AgNO_3$ is the oxidizing agent.

b. $\overset{+5}{V_2}\overset{-2}{O_5}(s) + 5\overset{0}{Ca}(l) \xrightarrow{\Delta} 2\overset{0}{V}(l) + 5\overset{+2}{Ca}\overset{-2}{O}(s)$

V in V_2O_5 is reduced, and V_2O_5 is the oxidizing agent. Ca in Ca(l) is oxidized, and Ca(l) is the reducing agent.

c. $\overset{+2}{Ca}\overset{+4}{C}\overset{-2}{O_3}(aq) + \overset{+4}{Si}\overset{-2}{O_2}(s) \rightarrow \overset{+2}{Ca}\overset{+4}{Si}\overset{-2}{O_3}(s) + \overset{+4}{C}\overset{-2}{O_2}(g)$

Not redox

d. $2\overset{+1}{Na}\overset{-1}{H}(s) \xrightarrow{\Delta} 2\overset{0}{Na}(s) + \overset{0}{H_2}(g)$

Na in NaH is reduced, and NaH (or Na^+ in NaH) is the oxidizing agent.

H in NaH is oxidized, and NaH (or H^- in NaH) is also the reducing agent.

+3 –2 +1 +7 –2 +1 –2 +1 –1

e. $5As_4O_6(s) + 8KMnO_4(aq) + 18H_2O(l) + 52KCl(aq)$

+1 +5 –2 +2 –1 +1 –1

$\rightarrow\ 20K_3AsO_4(aq) + 8MnCl_2(aq) + 36HCl(aq)$

As in As_4O_6 is oxidized, and As_4O_6 is the reducing agent. Mn in $KMnO_4$ is reduced, and $KMnO_4$ is the oxidizing agent.

53. The following equations summarize the steps in the process used to make most of the sulfuric acid produced in the United States. Determine the oxidation number for each atom in each of the following equations, and indicate whether each reaction is a redox reaction. For the redox reactions, identify what is oxidized, what is reduced, the oxidizing agent, and the reducing agent. *(Objs 3-6)*

0 0 +4 –2

$1/8S_8 + O_2 \rightarrow SO_2$

Yes, it's redox.

S atoms in S_8 are oxidized, O atoms in O_2 are reduced, O_2 is the oxidizing agent, and S_8 is the reducing agent.

+4 –2 0 +6 –2

$SO_2 + ½O_2 \rightarrow SO_3$

Yes, it's redox.

S atoms in SO_2 are oxidized, O atoms in O_2 are reduced, O_2 is the oxidizing agent, and SO_2 is the reducing agent.

+6 –2 +1 –2 +1 +6 –2

$SO_3 + H_2O \rightarrow H_2SO_4$

Because none of the atoms change their oxidation number, this is **not redox***.*

Section 6.3 Types of Chemical Reactions

55. Classify each of these reactions as a combination reaction, a decomposition reaction, a combustion reaction, or a single-displacement reaction. *(Obj 7)*

a. $2NaH(s) \rightarrow 2Na(s) + H_2(g)$ **decomposition**

b. $2KI(aq) + Cl_2(g) \rightarrow 2KCl(aq) + I_2(s)$ **single-displacement**

c. $2C_2H_5SH(l) + 9O_2(g) \rightarrow 4CO_2(g) + 6H_2O(l) + 2SO_2(g)$ **combustion**

d. $H_2(g) + CuO(s) \xrightarrow{\Delta} Cu(s) + H_2O(l)$ **single-displacement**

e. $P_4(s) + 5O_2(g) \rightarrow P_4O_{10}(s)$ **combination and combustion**

57. Classify each of these reactions as a combination reaction, a decomposition reaction, a combustion reaction, or a single-displacement reaction. *(Obj 7)*

a. $4B(s) + 3O_2(g) \rightarrow 2B_2O_3(s)$ **combination and combustion**

b. $(C_2H_5)_2O(l) + 6O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l)$ **combustion**

c. $2Cr_2O_3(s) + 3Si(s) \xrightarrow{\Delta} 4Cr(s) + 3SiO_2(s)$ **single-displacement**

d. $C_6H_{11}SH(l) + 10O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l) + SO_2(g)$ **combustion**

e. $2NaHCO_3(s) \xrightarrow{\Delta} Na_2CO_3(s) + H_2O(l) + CO_2(g)$ **decomposition**

59. Write balanced equations for the complete combustion of each of the following substances. (Obj 8)

    a. $C_3H_8(g)$ **$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$**

    b. $C_4H_9OH(l)$ **$C_4H_9OH(l) + 6O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l)$**

    c. $CH_3COSH(l)$ **$CH_3COSH(l) + 7/2O_2(g) \rightarrow 2CO_2(g) + 2H_2O(l) + SO_2(g)$**
    or $2CH_3COSH(l) + 7O_2(g) \rightarrow 4CO_2(g) + 4H_2O(l) + 2SO_2(g)$

61. The following pairs react in single-displacement reactions that are similar to the reaction between uncharged zinc metal and the copper(II) ions in a copper(II) sulfate solution. Describe the changes in these reactions, including the nature of the particles in the system before the reaction takes place, the nature of the reaction itself, and the nature of the particles in the system after the reaction. Your description should also include the equations for the half-reactions and the net ionic equation for the overall reaction. (Obj 9)

    a. magnesium metal and nickel(II) nitrate, $Ni(NO_3)_2(aq)$

    Because nickel(II) nitrate is a water soluble ionic compound, the $Ni(NO_3)_2$ solution contains Ni^{2+} ions surrounded by the negatively charged oxygen ends of water molecules and separate NO_3^- ions surrounded by the positively charged hydrogen ends of water molecules. These ions move throughout the solution colliding with each other, with water molecules, and with the walls of their container. When solid magnesium is added to the solution, nickel ions begin to collide with the surface of the magnesium. When each Ni^{2+} ion collides with an uncharged magnesium atom, two electrons are transferred from the magnesium atom to the nickel(II) ion. Magnesium ions go into solution, and uncharged nickel solid forms on the surface of the magnesium. See Figure 6.4. Picture Ni^{2+} in the place of Cu^{2+} and magnesium metal in the place of zinc metal.

    Because the magnesium atoms lose electrons and change their oxidation number from 0 to +2, they are oxidized and act as the reducing agent. The Ni^{2+} ions gain electrons and decrease their oxidation number from +2 to 0, so they are reduced and act as the oxidizing agent. The half reaction equations and the net ionic equation for this reaction are below.

    oxidation: $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$

    reduction: $Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$

    Net ionic equation: $Mg(s) + Ni^{2+}(aq) \rightarrow Mg^{2+}(aq) + Ni(s)$

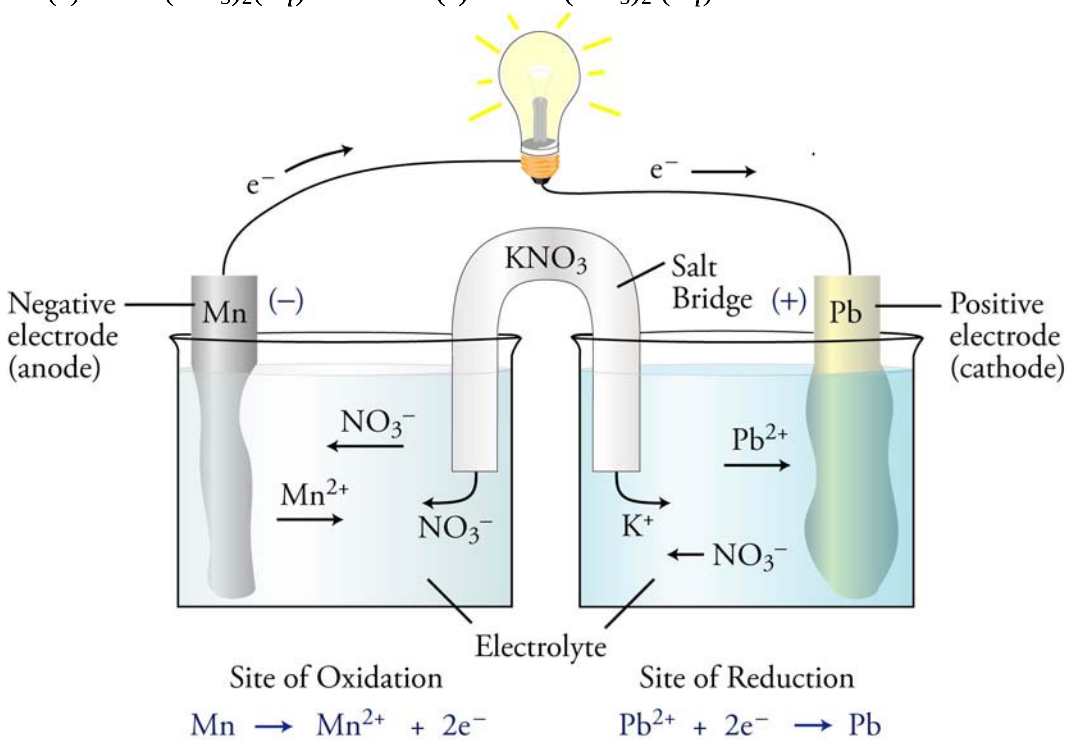
Section 6.4 Voltaic Cells

62. We know that the following reaction can be used to generate an electric current in a voltaic cell.

    Zn(s) + $CuSO_4$(aq) → Cu(s) + $ZnSO_4$(aq)

    Sketch similar voltaic cells made from each of the reactions presented below, showing the key components of the two half-cells and indicating the cathode electrode and the anode electrode, the negative and positive electrodes, the direction of movement of the electrons in the wire between the electrodes, and the direction of movement of the ions in the system. Show a salt bridge in each sketch, and show the movement of ions out of the salt bridge. *(Objs 10 & 11)*

    a. Mn(*s*) + $Pb(NO_3)_2$(*aq*) → Pb(*s*) + $Mn(NO_3)_2$ (*aq*)



The voltaic cell that utilizes the redox reaction between manganese metal and lead(II) ions is composed of two half-cells. The first half-cell consists of a strip of manganese metal in a solution of manganese(II) nitrate. The second half-cell consists of a strip of lead metal in a solution of lead(II) nitrate. In the Mn/Mn^{2+} half-cell, manganese atoms lose two electrons and are converted to manganese ions. The electrons pass through the wire to the Pb/Pb^{2+} half-cell where Pb^{2+} ions gain the two electrons to form uncharged lead atoms. Mn is oxidized to Mn^{2+} at the manganese electrode, so this electrode is the anode. Pb^{2+} ions are reduced to uncharged lead atoms at the lead strip, so metallic lead is the cathode.

63. The following equation summarizes the chemical changes that take place in a typical dry cell.

$$Zn(s) + 2MnO_2(s) + 2NH_4^+(aq) \rightarrow Zn^{2+}(aq) + Mn_2O_3(s) + 2NH_3(aq) + H_2O(l)$$

Determine the oxidation number for each atom in this equation, and identify what is oxidized, what is reduced, the oxidizing agent, and the reducing agent. (Objs 3-6)

0 +4 −2 −3 +1 +2 +3 −2 −3 +1 +1 −2

$$\overset{0}{Zn}(s) + 2\overset{+4}{Mn}\overset{-2}{O_2}(s) + 2\overset{-3}{N}\overset{+1}{H_4^+}(aq) \rightarrow \overset{+2}{Zn^{2+}}(aq) + \overset{+3}{Mn_2}\overset{-2}{O_3}(s) + 2\overset{-3}{N}\overset{+1}{H_3}(aq) + \overset{+1}{H_2}\overset{-2}{O}(l)$$

Zn is oxidized and is the reducing agent. Mn in MnO_2 is reduced, so MnO_2 is the oxidizing agent.

65. The following equation summarizes the chemical changes that take place in a lead-acid battery. Determine the oxidation number for each atom in the equation, and identify what is oxidized, what is reduced, the oxidizing agent, and the reducing agent.
(Objs 3-6)

$$\overset{0}{Pb}(s) + \overset{+4}{Pb}\overset{-2}{O_2}(s) + 2\overset{+1}{H}\overset{+6}{S}\overset{-2}{O_4^-}(aq) + 2\overset{+1}{H_3}\overset{-2}{O^+}(aq) \rightarrow 2\overset{+2}{Pb}\overset{+6}{S}\overset{-2}{O_4}(s) + 4\overset{+1}{H_2}\overset{-2}{O}(l)$$

Pb is oxidized and is the reducing agent. Pb in PbO_2 is reduced, so PbO_2 is the oxidizing agent.

Additional Problems

67. Sodium hydrogen carbonate, $NaHCO_3$, best known as the active ingredient in baking soda, is used in several ways in food preparation. It is also added to animal feeds and used to make soaps and detergents. Baking soda can be used to put out small fires on your stovetop. The heat of the flames causes the $NaHCO_3$ to decompose to form carbon dioxide, which displaces the air above the flames depriving the fire of the oxygen necessary for combustion. The equation for this reaction is (Objs 3-5)

$$2\overset{+1}{Na}\overset{+1}{H}\overset{+4}{C}\overset{-2}{O_3}(s) \xrightarrow{\Delta} \overset{+4}{C}\overset{-2}{O_2}(g) + \overset{+1}{Na_2}\overset{+4}{C}\overset{-2}{O_3}(s) + \overset{+1}{H_2}\overset{-2}{O}(g)$$

Determine the oxidation number for each atom in this equation, and indicate whether the reaction is a redox reaction. If the reaction is redox, identify what is oxidized and what is reduced. (Objs 3-5)

Because none of the atoms change their oxidation number, this is **not redox**.

69. In the past, mercury batteries were commonly used to power electronic watches and small appliances. The overall reaction for this type of battery is

$$\overset{+2}{Hg}\overset{-2}{O}(s) + \overset{0}{Zn}(s) \rightarrow \overset{+2}{Zn}\overset{-2}{O}(s) + \overset{0}{Hg}(l)$$

Determine the oxidation number for each atom in the equation and decide whether the reaction is a redox reaction or not. If it is redox, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent.

Yes, it's redox.

Zn atoms in Zn(s) are oxidized, Hg atoms in HgO are reduced, HgO is the oxidizing agent, and Zn is the reducing agent.

71. $Mn_3(PO_4)_2$, which is used to make corrosion resistant coatings on steel, aluminum, and other metals, is made from the reaction of $Mn(OH)_2$ with H_3PO_4.

+2 –2 +1 +1 +5 –2 +2 +5 –2 +1 –2

$$3\overset{+2}{Mn}(\overset{-2}{O}\overset{+1}{H})_2(s) + 2\overset{+1}{H}_3\overset{+5}{P}\overset{-2}{O}_4(aq) \rightarrow \overset{+2}{Mn}_3(\overset{+5}{P}\overset{-2}{O}_4)_2(s) + 6\overset{+1}{H}_2\overset{-2}{O}(l)$$

Determine the oxidation number for each atom in the equation and identify whether the reaction is a redox reaction or not. If it is redox, identify what is oxidized, what is reduced, the oxidizing agent, and the reducing agent.

No, none of the atoms change their oxidation number, so it's not redox.

73. The *noble* gases in group 18 on the periodic table used to be called the *inert* gases because they were thought to be incapable of forming compounds. Their name has been changed to noble gases because although they resist combining with the more common elements to their left on the periodic table, they do mingle with them on rare occasions. The following equations describe reactions that form xenon compounds. Determine the oxidation number for each atom in the reactions, and identify each reaction as redox or not. If it is redox, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent.

$$\overset{0}{Xe} + 3\overset{0}{F}_2 \rightarrow \overset{+6}{Xe}\overset{-1}{F}_6$$

Yes, it's redox.

Xe atoms are oxidized, F atoms in F_2 are reduced, F_2 is the oxidizing agent, and Xe is the reducing agent.

$$\overset{+6}{Xe}\overset{-1}{F}_6 + \overset{+1}{H}_2\overset{-2}{O} \rightarrow \overset{+6}{Xe}\overset{-2}{O}\overset{-1}{F}_4 + 2\overset{+1}{H}\overset{-1}{F}$$

None of the atoms change their oxidation number, so it's not redox.

$$\overset{+6}{Xe}\overset{-1}{F}_6 + \overset{-2}{O}\overset{+5}{P}\overset{-1}{F}_3 \rightarrow \overset{+6}{Xe}\overset{-2}{O}\overset{-1}{F}_4 + \overset{+5}{P}\overset{-1}{F}_5$$

None of the atoms change their oxidation number, so it's not redox.

75. Sodium perbromate is an oxidizing agent that can be made in the two ways represented by the equations below. The first equation shows the way it was made in the past, and the second equation represents the technique used today. Determine the oxidation number for each atom in each of these equations, and decide whether each reaction is a redox reaction or not. If a reaction is a redox reaction, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent.

$$\overset{+1}{Na}\overset{+5}{Br}\overset{-2}{O}_3 + \overset{+2}{Xe}\overset{-1}{F}_2 + \overset{+1}{H}_2\overset{-2}{O} \rightarrow \overset{+1}{Na}\overset{+7}{Br}\overset{-2}{O}_4 + 2\overset{+1}{H}\overset{-1}{F} + \overset{0}{Xe}$$

Yes, it's redox.

Br atoms in $NaBrO_3$ are oxidized, Xe atoms in XeF_2 are reduced, XeF_2 is the oxidizing agent, and $NaBrO_3$ is the reducing agent.

$$\overset{+1}{Na}\overset{+5}{Br}\overset{-2}{O}_3 + \overset{0}{F}_2 + 2\overset{+1}{Na}\overset{-2}{O}\overset{+1}{H} \rightarrow \overset{+1}{Na}\overset{+7}{Br}\overset{-2}{O}_4 + 2\overset{+1}{Na}\overset{-1}{F} + \overset{+1}{H}_2\overset{-2}{O}$$

Yes, it's redox.

Br atoms in $NaBrO_3$ are oxidized, F atoms in F_2 are reduced, F_2 is the oxidizing agent, and $NaBrO_3$ is the reducing agent.

77. The following equations represent reactions that involve only halogen atoms. Iodine pentafluoride, IF_5, is used to add fluorine atoms to other compounds, bromine pentafluoride, BrF_5 is an oxidizing agent in liquid rocket propellants, and chlorine trifluoride, ClF_3, is used to reprocess nuclear reactor fuels. Determine the oxidation number for each atom in these equations, and decide whether each reaction is a redox reaction or not. If a reaction is a redox reaction, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent.

$$\overset{+1\,-1}{\mathrm{IF}}(g) + 2\overset{0}{\mathrm{F}}_2(g) \rightarrow \overset{+5\,-1}{\mathrm{IF}}_5(l)$$

Yes, it's redox. I atoms in IF are oxidized, F atoms in F_2 are reduced, F_2 is the oxidizing agent, and IF is the reducing agent.

$$\overset{+1\,-1}{\mathrm{BrF}}(g) + 2\overset{0}{\mathrm{F}}_2(g) \rightarrow \overset{+5\,-1}{\mathrm{BrF}}_5(g)$$

Yes, it's redox. Br atoms in BrF are oxidized, F atoms in F_2 are reduced, F_2 is the oxidizing agent, and BrF is the reducing agent.

$$\overset{0}{\mathrm{Cl}}_2(g) + 3\overset{0}{\mathrm{F}}_2(g) \rightarrow 2\overset{+3\,-1}{\mathrm{ClF}}_3(g)$$

Yes, it's redox. Cl atoms in Cl_2 are oxidized, F atoms in F_2 are reduced, F_2 is the oxidizing agent, and Cl_2 is the reducing agent.

79. Sodium sulfate, which is used to make detergents and glass, is formed in the following reaction.

$$4\overset{+1\,-1}{\mathrm{NaCl}} + 2\overset{+4\,-2}{\mathrm{SO}}_2 + 2\overset{+1\,-2}{\mathrm{H_2O}} + \overset{0}{\mathrm{O}}_2 \rightarrow 2\overset{+1\,+6\,-2}{\mathrm{Na_2SO_4}} + 4\overset{+1\,-1}{\mathrm{HCl}}$$

Determine the oxidation number for each atom in the equation and decide whether the reaction is a redox reaction or not. If a reaction is a redox reaction, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent.

Yes, it's redox. S atoms in SO_2 are oxidized, O atoms in O_2 are reduced, O_2 is the oxidizing agent, and SO_2 is the reducing agent.

81. Elemental sulfur is produced by the chemical industry from naturally occurring hydrogen sulfide in the following steps. Determine the oxidation number for each atom in these equations and decide whether each reaction is a redox reaction or not. If a reaction is a redox reaction, identify which substance is oxidized, which substance is reduced, the oxidizing agent, and the reducing agent.

$$2\overset{+1\,-2}{\mathrm{H_2S}} + 3\overset{0}{\mathrm{O}}_2 \rightarrow 2\overset{+4\,-2}{\mathrm{SO}}_2 + 2\overset{+1\,-2}{\mathrm{H_2O}}$$

Yes, it's redox. S atoms in H_2S are oxidized, O atoms in O_2 are reduced, O_2 is the oxidizing agent, and H_2S is the reducing agent.

$$\overset{+4\,-2}{\mathrm{SO}}_2 + 2\overset{+1\,-2}{\mathrm{H_2S}} \rightarrow 3\overset{0}{\mathrm{S}} + 2\overset{+1\,-2}{\mathrm{H_2O}}$$

Yes, it's redox. S atoms in H_2S are oxidized, S atoms in SO_2 are reduced, SO_2 is the oxidizing agent, and H_2S is the reducing agent.

83. Leaded gasoline, originally developed to decrease pollution, is now banned because the lead(II) bromide, $PbBr_2$, emitted when it burns decomposes in the atmosphere into two serious pollutants, lead and bromine. The equation for this reaction follows. Determine the oxidation number for each atom in the equation, and indicate whether the reaction is a redox reaction. If the reaction is redox, identify what is oxidized and what is reduced. *(Objs 3-5)*

$$\overset{+2\ -1}{PbBr_2} \xrightarrow{\text{sunlight}} \overset{0}{Pb} + \overset{0}{Br_2}$$

Yes, it's redox. Br atoms in $PbBr_2$ are oxidized, and Pb atoms in $PbBr_2$ are reduced.

85. When the calcium carbonate, $CaCO_3$, in limestone is heated to a high temperature, it decomposes into calcium oxide (called lime or quicklime) and carbon dioxide. Lime was used by the early Romans, Greeks, and Egyptians to make cement, and it is used today to make over 150 different chemicals. In another reaction, calcium oxide and water form calcium hydroxide, $Ca(OH)_2$ (called slaked lime), which is used to remove the sulfur dioxide from smokestacks above power plants that burn high-sulfur coal. The equations for all these reactions follow. Determine the oxidation number for each atom in the equations, and indicate whether the reactions are redox reactions. For each redox reaction, identify what is oxidized and what is reduced. *(Objs 3-5)*

$$\overset{+2\ +4\ -2}{CaCO_3} \rightarrow \overset{+2\ -2}{CaO} + \overset{+4\ -2}{CO_2}$$

$$\overset{+2\ -2}{CaO} + \overset{+1\ -2}{H_2O} \rightarrow \overset{+2\ -2\ +1}{Ca(OH)_2}$$

$$\overset{+4\ -2}{SO_2} + \overset{+1\ -2}{H_2O} \rightarrow \overset{+1\ +4\ -2}{H_2SO_3}$$

$$\overset{+2\ -2\ +1}{Ca(OH)_2} + \overset{+1\ +4\ -2}{H_2SO_3} \rightarrow \overset{+2\ +4\ -2}{CaSO_3} + \overset{+1\ -2}{2H_2O}$$

Because none of the atoms change their oxidation number, **none of these reactions are redox reactions**.

87. The space shuttle's solid rocket boosters get their thrust from the reaction of aluminum metal with ammonium perchlorate, NH_4ClO_4, which generates a lot of gas and heat. The billowy white smoke is due to the formation of very finely divided aluminum oxide solid. One of the reactions that takes place is

$$\overset{0}{10Al(s)} + \overset{-3\ +1\ +7\ -2}{6NH_4ClO_4(s)} \rightarrow \overset{+3\ -2}{5Al_2O_3(s)} + \overset{+1\ -1}{6HCl(g)} + \overset{0}{3N_2(g)} + \overset{+1\ -1}{9H_2O(g)}$$

Is this a redox reaction? What is oxidized and what is reduced? *(Obj 3-5)*

Yes, it's redox. Al atoms in Al and N atoms in NH_4ClO_4 are oxidized, and Cl atoms in NH_4ClO_4 are reduced.

89. Determine the oxidation number for each atom in the following equations and decide whether each reaction is a redox reaction or not. If a reaction is redox, identify which substance is oxidized, which is reduced, the oxidizing agent, and the reducing agent.

a. $\overset{+1\ +6\ -2}{K_2Cr_2O_7(aq)} + \overset{+1\ -1}{14HCl(aq)} \rightarrow \overset{+1\ -1}{2KCl(aq)} + \overset{+3\ -1}{2CrCl_3(aq)} + \overset{+1\ -2}{7H_2O(l)} + \overset{0}{3Cl_2(g)}$

Yes, it is redox. Cl in HCl is oxidized, Cr in $K_2Cr_2O_7$ is reduced, HCl is the reducing agent, and $K_2Cr_2O_7$ is the oxidizing agent.

b. $\overset{0}{Ca(s)} + \overset{+1\ -2}{2H_2O(l)} \rightarrow \overset{+2\ -2\ +1}{Ca(OH)_2(s)} + \overset{0}{H_2(g)}$

Yes, it is redox. Ca is oxidized, H in H_2O is reduced, Ca is the reducing agent, and H_2O is the oxidizing agent.

91. For each of the following equations, determine the oxidation number for each atom in the equation, and indicate whether the reaction is a redox reaction. If the reaction is redox, identify what is oxidized, what is reduced, the oxidizing agent, and the reducing agent. *(Objs 3-6)*

a. $\overset{0}{Ca}(s) + \overset{0}{F_2}(g) \rightarrow \overset{+2}{Ca}\overset{-1}{F_2}(s)$

Yes, it's redox. Ca is oxidized and is the reducing agent. F in F_2 is reduced, and F_2 is the oxidizing agent.

b. $2\overset{0}{Al}(s) + 3\overset{+1}{H_2}\overset{-2}{O}(g) \xrightarrow{\Delta} \overset{+3}{Al_2}\overset{-2}{O_3}(s) + 3\overset{0}{H_2}(g)$

Yes, it's redox. Al is oxidized and is the reducing agent. H in H_2O is reduced, so H_2O is the oxidizing agent.

93. The following equations represent reactions used by the U.S. chemical industry. Classify each as a combination reaction, a decomposition reaction, a combustion reaction, or a single-displacement reaction. *(Obj 7)*

a. $P_4 + 5O_2 + 6H_2O \rightarrow 4H_3PO_4$ **combination**

b. $TiCl_4 + O_2 \rightarrow TiO_2 + 2Cl_2$ **single-displacement**

c. $CH_3CH_3 \xrightarrow{\Delta} CH_2CH_2 + H_2$ **decomposition**

95. Write a balanced equation for the redox reaction of carbon dioxide gas and hydrogen gas to form carbon solid and water vapor.

$\mathbf{CO_2(g) + 2H_2(g) \rightarrow C(s) + 2H_2O(g)}$

97. Titanium metal is used to make metal alloys for aircraft, missiles, and artificial hip joints. It is formed in the reaction of titanium(IV) chloride with magnesium metal. The other product is magnesium chloride. Write a balanced equation, without including states, for this redox reaction.

$\mathbf{TiCl_4 + 2Mg \rightarrow Ti + 2MgCl_2}$

99. Write a balanced equation for the redox reaction of solid potassium with liquid water to form aqueous potassium hydroxide and hydrogen gas.

$\mathbf{2K(\mathit{s}) + 2H_2O(\mathit{l}) \rightarrow 2KOH(\mathit{aq}) + H_2(\mathit{g})}$

101. Write a balanced equation for the redox reaction of calcium metal and bromine liquid to form solid calcium bromide.

$\mathbf{Ca(\mathit{s}) + Br_2(\mathit{l}) \rightarrow CaBr_2(\mathit{s})}$

103. Magnesium chloride is used to make disinfectants, fire extinguishers, paper, and floor sweeping compounds. It is made from the reaction of hydrochloric acid with solid magnesium hydroxide. Write a balanced equation for this reaction, which yields aqueous magnesium chloride and liquid water.

$\mathbf{2HCl(\mathit{aq}) + Mg(OH)_2(\mathit{s}) \rightarrow MgCl_2(\mathit{aq}) + 2H_2O(\mathit{l})}$