2.2 The Gain and Loss of Electrons

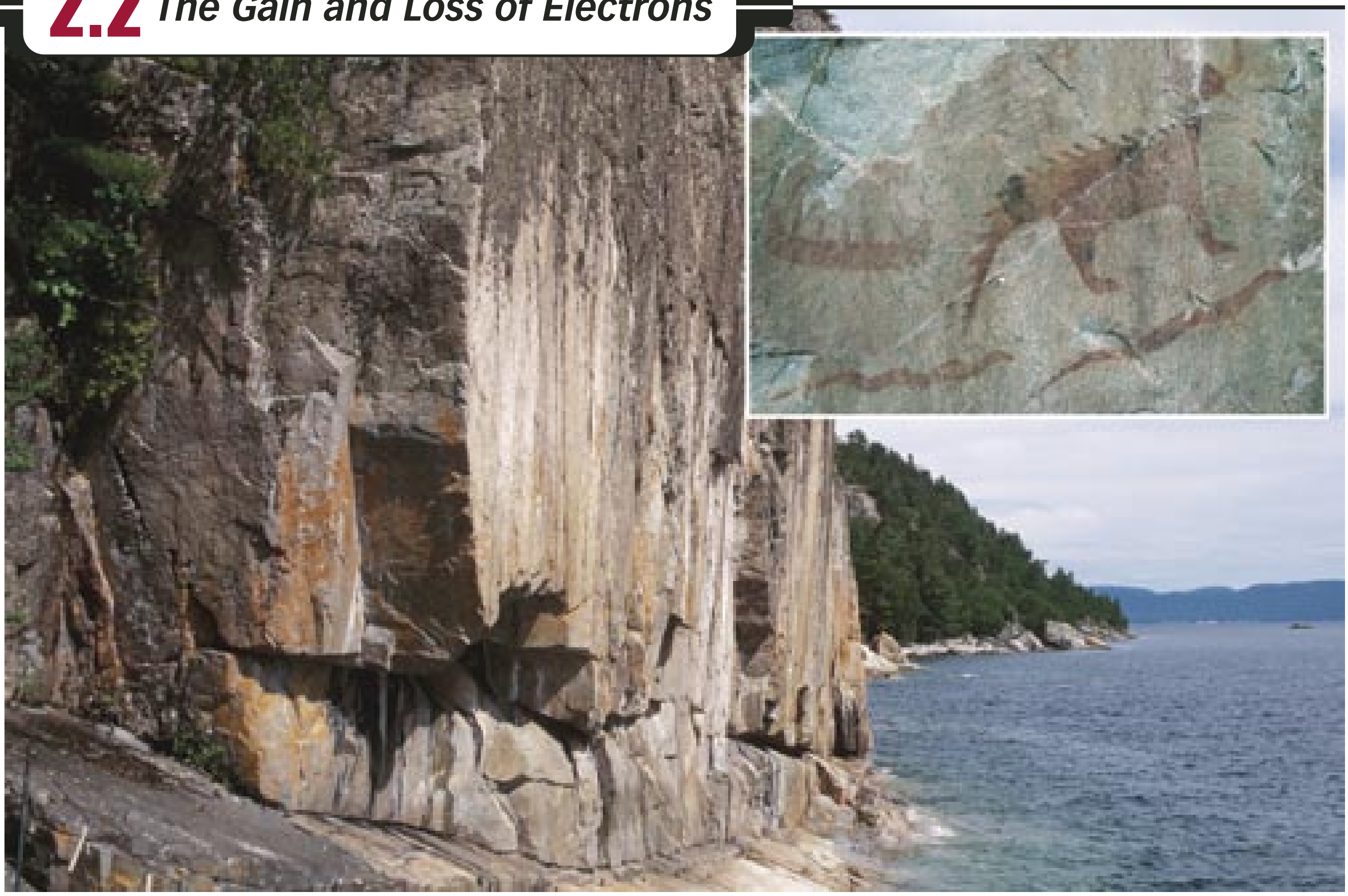

Figure A2.7: These rock paintings are found on the face of Agawa Rock on the shores of Lake Superior. They were painted hundreds of years ago by the ancestors of Anishinabe people.

One great holiday adventure is exploring the eastern shoreline of Lake Superior by kayak or canoe. One of the highlights of such a trip is to visit Agawa Rock, the site of centuries-old paintings by ancestors of Anishinabe, or Ojibway, people. Painted by using a paste of red ochre, $Fe_2O_3(aq)$, the images shown in Figure A2.7 include a canoe, two serpents, and Mishipeshu, a great "horned," underwater lynx that symbolizes the treacherous nature of dark and turbulent waters. Elders from the nearby community have explained that images like these serve many purposes: recounting important events (such as a great battle), as symbols for the clan or family group that lived nearby, or as symbols of spiritual significance. In the language of the Anishinabe people, *Agawa* means "sacred place." So, if you are able to visit this site, it is important to treat it with respect and recognize that it is an important place in Canada's national heritage.

By canoeing to other sites along the lakeside, you can encounter even older archaeological evidence left by the ancestors of the Anishinabe people. The most noteworthy would be abandoned copper mines that are thousands of years old. Natural outcroppings of very pure copper—about 99%—were mined long ago and were the source of most of the copper that was traded across North America by First Nations people for thousands of years.

Copper artifacts, similar to those described in Lesson 2.1, have been found at sites along the Clearwater River in northern Alberta and Saskatchewan. Archaeologists have determined these artifacts to be between 3500 and 5000 years old. The high purity of the copper in these objects, as well as the identification of tiny amounts of specific trace elements, has enabled archaeologists to establish that the copper originated from deposits along the shores of Lake Superior.

Today, mining operations extract copper from rock that may have less than 2% copper in the **ore**. These deposits are frequently contaminated with significant quantities of iron and other minerals. This means that vast quantities of rock have to be mined, crushed into a fine powder, and heated in huge furnaces to separate the copper from the unwanted minerals.

ore: a rock that contains a useful metal in a sufficient concentration that makes it economical to mine

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The copper that emerges from the first set of furnaces is in the form of copper(I) sulfide. The molten copper(I) sulfide is then treated in another furnace by blowing air over it to remove the sulfur. This process results in a product called blister copper, because its surface appears blistered due to escaping sulfur dioxide gas while it is solidifying. Blister copper is 97% to 99% pure. The following two reactions occur as air is blown over molten copper sulfide to produce blister copper:

Reaction 1: $2\,Cu_2S(l) + 3\,O_2(g) \rightarrow 2\,Cu_2O(l) + 2\,SO_2(g)$
Reaction 2: $2\,Cu_2O(l) + Cu_2S(l) \rightarrow 6\,Cu(l) + SO_2(g)$

Figure A2.8: Blister copper is poured after being removed from a furnace.

Practice

12. Ores containing less than 2% copper are being mined because rock formations with higher concentrations of copper have already been removed. Even if over 98% of the ore is waste rock, all of this waste material must still be mined, crushed, ground up into a very fine powder, and subjected to extreme heat in furnaces to recover the copper.

- **a.** The mining industry in Canada accounts for over 9% of electricity used in Canada. Explain why this sector of the economy is such a major consumer of energy.
- **b.** If a mine produces 150 000 t of blister copper every year, approximately how many tonnes of finely ground waste rock are produced every year?
- **c.** Approximately 50% of the copper being manufactured is processed from recycled copper. Suggest reasons why recycled copper is likely to become an even more important source of copper in the future.

13. Refer to Reaction 2 above. A copper-refining operation produces about 74.8 mol of copper metal every second.

- **a.** Determine the number of moles of copper(I) sulfide required every second.
- **b.** Determine the number of moles of sulfur dioxide produced every second.

Copper: Essential for Using Electricity and Water

In Canada and across the world, more than half of the copper produced is used for wiring in a wide variety of applications: household wiring, electric motors, transformers, and generators to name a few. The second largest use of copper is the brass mill industry that makes copper pipes and fixtures for plumbing and other applications. So, every time you take a shower or use a small motor in a tool or appliance, you are using technologies that directly depend on the production of copper.

Figure A2.9: Copper plays a big part in home construction, from wiring to plumbing.

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Ores Containing Other Metals

Like copper, most metals are not found naturally in a pure form. Instead, they are usually found in rock formations as ores. The metal atoms in an ore are bonded to non-metal atoms—often oxygen or sulfur—in ionic compounds. As you discovered in Chapter 1, metal ions in compounds have lost electrons and, therefore, have positive charges.

Figure A2.10: This sample is almost entirely made up of pure copper.

Practice

14. Copy and complete the following table. A copy of this table is available as a handout on the Science 20 Textbook CD.

METAL IONS

Ore Compound	Chemical Formula	Metal Ion	Number of Electrons Lost by Metal Ion
aluminium oxide	$Al_2O_3(s)$	$Al^{3+}(aq)$	
iron(III) oxide	$Fe_2O_3(s)$		3
silver oxide	$Ag_2O(s)$	$Ag^{+}(aq)$	
silver sulfide	$Ag_2S(s)$		1
iron(II) sulfide	$FeS(s)$	$Fe^{2+}(aq)$	
zinc nitrate	$Zn(NO_3)_2(s)$		2
calcium carbonate	$CaCO_3(s)$	$Ca^{2+}(aq)$	
potassium phosphate	$K_3PO_4(s)$		1

The Transfer of Electrons

Why is it that metals are usually found locked up in ionic compounds in ore deposits? Why are outcrops of pure metal so rare? Recall from Chapter 1 that the most stable arrangement for metals is to have their outer energy levels resemble those of noble gases. This stability can be achieved by a metal combining with a non-metal.

Silver atoms, for example, can combine with sulfur atoms under a variety of conditions: as extreme as inside a volcano or as ordinary as a silver spoon sitting on a kitchen counter. As shown in Figure A.2.11, in both cases, this process involves a transfer of electrons from the metal to the non-metal.

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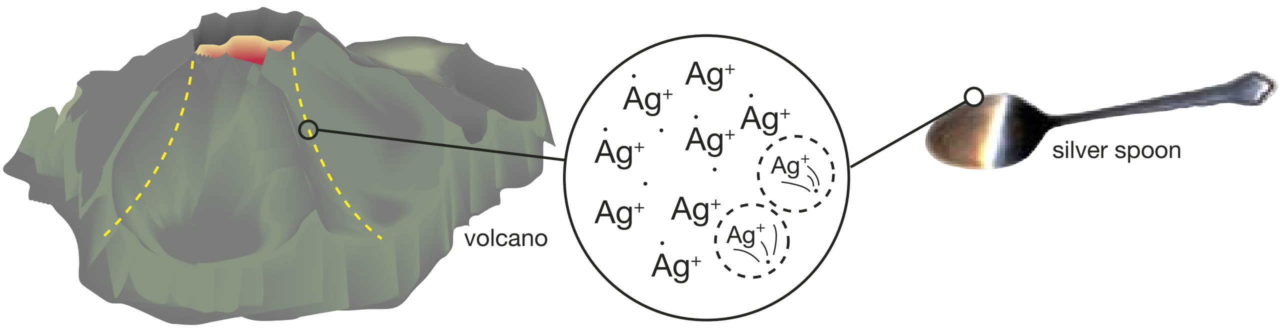
How a Metal Becomes an Ionic Compound

A metal is made up of positively charged particles within a "sea" of free-floating electrons.

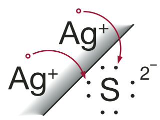


Occasionally, some of the free-floating electrons are lost to other atoms in the environment. The loss of these electrons turns the metal atoms into positively charged ions.

$$2 \times \left[Ag(s) \rightarrow Ag^{+}(aq) + 1e^{-} \right]$$

silver metal	silver ion	one electron

The positive metal ions are then attracted to negative ions that have received the electron.



This ionic compound forms a crystal structure that is the black tarnish on a silver surface.

Figure A2.11: The process of forming an ionic crystal involves the exchange of electrons.

Oxidation: The Loss of Electrons

When an atom loses electrons it undergoes a process called **oxidation**. Originally, *oxidation* meant any reaction involving oxygen, but the term has been expanded to include any chemical process in which one substance transfers electrons to another substance.

oxidation: a chemical process involving the loss of electrons

Examples of Oxidation Reactions

Neutral atoms lose electrons and become positively charged ions.

$$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^{-}$$

metal atom	metal ion	two electrons

Negatively charged ions lose electrons to become neutral atoms.

$$Cl^{-}(aq) \rightarrow Cl(g) + 1e^{-}$$

non-metal negative ion	non-metal atom	one electron

Positively charged ions lose electrons to become even more positively charged.

$$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + 1e^{-}$$

positive metal ion	a more positive metal ion	one electron

Practice

15. Examine Figure A2.11.

a. Identify the substance that was oxidized.

b. Explain why this is called oxidation even though oxygen was not involved.

c. If the magma within a volcano remains liquid for a long time, the metallic elements may settle in layers according to density within the magma chamber—the heavier the element, the deeper it is found. This settling of magma acts to concentrate the metals into valuable ores. Why are the geological remains of ancient volcanoes often the sites of copper mines?

16. Consider the examples of oxidation reactions.

a. Identify the common feature on the right side of each reaction.

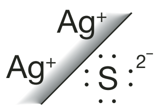
b. Why does the term *oxidation* have the potential to be misleading?

Reducing Large Amounts of Ore to Pure Metal

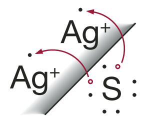
It takes 1000 kg of ore to produce less than 20 kg of pure copper. The essential task of the process is to reverse the oxidation reaction that has locked the copper metal into compounds like copper sulfide. Processing silver is also a matter of reversing oxidation. But, in this case, the task of reducing the amount of material is even greater: 1000 kg of ore usually yields about 0.1 kg of pure silver.

Purifying Metals from Metal Compounds

In ore deposits, metals are frequently locked up in ionic compounds.



In the process of refining the ore, the metallic ions are given back the electrons they lost.



This process purifies the metal since it is no longer part of the ionic compound.

$$2 \times [Ag^{+} + 1e^{-} \rightarrow Ag(s)]$$

silver ion — one electron — silver metal

Figure A2.12: Purifying metals involves giving back electrons to metal ions.

Reduction: The Gain of Electrons

In Figure A2.12, silver ions gained electrons to form pure silver. When atoms gain electrons, they are undergoing a process called **reduction**. At first glance, the name seems to have things backward. How can a gain of electrons be a reduction? Historically, the name *reduction* comes from the metal-refining industry, where the application of this process involves reducing very large amounts of ore to smaller amounts of pure metal. As the following examples indicate, the term *reduction* has been expanded to include any reaction in which there is a gain of electrons.

reduction: a chemical process involving a gain of electrons

Practice

17. Examine Figure A2.12.

a. Identify the substance that is reduced.

b. Recall the process of silver tarnishing and the process of chemically removing the tarnish. Which of these two processes is an example of reduction?

Examples of Reduction Reactions

Neutral atoms gain electrons to become ions.

$$Cl_2(g) + 2e^{-} \rightarrow 2Cl^{-}(aq)$$

non-metal molecule — two electrons — non-metal negative ion

Positively charged ions gain electrons to become neutral atoms.

$$Na^{+}(aq) + 1e^{-} \rightarrow Na(s)$$

positive metal ion — one electron — metal atom

Positively charged ions gain electrons to become less positively charged.

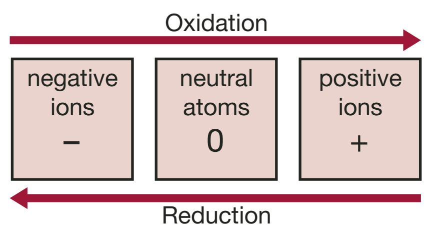
$$Fe^{3+}(aq) + 1e^{-} \rightarrow Fe^{2+}(aq)$$

positive metal ion — one electron — a less positive metal ion

Hints for Keeping It All Straight

You can use the following hints to remember the definitions and circumstances of oxidation and reduction reactions:

- **OIL RIG**: These two words are a memory device to help you remember the definitions.
  "**O**xidation **i**s the **l**oss of electrons. **R**eduction **i**s the **g**ain of electrons."
- The following may help you identify a process as an oxidation or a reduction.



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Practice

18. For each of the following reactions, determine whether it is an oxidation or a reduction. Also, determine the number of electrons gained or lost.

- **a.** A silver ion, $Ag^{+}(aq)$, becomes a silver atom, $Ag(s)$.
- **b.** An iron metal atom, $Fe(s)$, becomes an iron(III) ion, $Fe^{3+}(aq)$.
- **c.** $Cl_2(g) \rightarrow 2\ Cl^{-}(aq)$
- **d.** $Au^{3+}(aq) \rightarrow Au(s)$
- **e.** $Sn(s) \rightarrow Sn^{4+}(aq)$
- **f.** $2\ F^{-}(aq) \rightarrow F_2(g)$
- **g.** $Fe^{2+}(aq) \rightarrow Fe^{3+}(aq)$
- **h.** $O_2(g) \rightarrow 2\ O^{2-}(aq)$
- **i.** $Sn^{4+}(aq) \rightarrow Sn^{2+}(aq)$
- **j.** $Na^{+}(aq) \rightarrow Na(s)$

19. Recall the activity on page 59 where you observed the reaction between zinc and silver nitrate in which pure silver was produced at the site of the reaction. Was the silver in this reaction oxidized or reduced?

Single Replacement Reactions

Refining copper ore to produce the pure copper metal that can be made into useful products involves reduction. Clearly, if reduction is a chemical process that involves a gain of electrons, another substance must lose electrons.

In the activity at the beginning of this chapter, you observed a chemical reaction. In Example Problem 2.3, each substance that participates in the reaction must be carefully analyzed to determine whether oxidation or reduction occurred.

Figure A2.12: This magnified photo shows evidence of chemical change as silver nitrate reacts with solid zinc.

Example Problem 2.3

A silver nitrate solution reacts with solid zinc to produce zinc nitrate solution and solid silver.

a. Write a balanced chemical reaction that describes this reaction.

b. Carefully examine each substance before and after the reaction to determine whether oxidation or reduction occurred. Use half-reactions to support your answers.

Solution

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

b. **Silver**

Before reaction: $Ag^{+}(aq)$

After reaction: $Ag(s)$

Since the silver started as a silver ion and became a pure metal atom, it must have gained an electron. Therefore, the silver was reduced.

$$2 \times \left[Ag^{+}(aq) + 1e^{-} \rightarrow Ag(s) \right]$$

Zinc

Before reaction: $Zn(s)$

After reaction: $Zn^{2+}(aq)$

Since the zinc started as a pure metal atom and became a zinc ion, it must have lost electrons. Therefore, the zinc was oxidized.

$$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^{-}$$

Nitrate Ion

Before reaction: $NO_3^{-}(aq)$

After reaction: $NO_3^{-}(aq)$

Since the nitrate ion remained the same, it did not undergo oxidation or reduction.

In Example Problem 2.3, the zinc replaced the silver ions in the silver nitrate, resulting in the production of solid silver. This reaction is an example of a **single replacement reaction**. Since the nitrate ion did not change, remaining an ion in the solution, it is called a **spectator**. Keep these terms in mind as you attempt the next Practice questions.

single replacement reaction: a reaction in which an element reacts with a compound to produce a new element and a new compound

spectator: an atom or polyatomic ion that does not change in a chemical reaction

Practice

20. Examine each balanced chemical equation, and identify the chemical substance being oxidized, the chemical substance being reduced, and any spectators.
    - **a.** $Zn(s) + 2\ HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$
    - **b.** $3\ MnO_2(s) + 4\ Al(s) \rightarrow 3\ Mn(s) + 2\ Al_2O_3(s)$
    - **c.** $2\ Al(s) + 3\ I_2(s) \rightarrow 2\ AlI_3(s)$
    - **d.** $2\ Na(s) + Cl_2(g) \rightarrow 2\ NaCl(s)$
    - **e.** $Ca(s) + 2\ HOH(l) \rightarrow Ca(OH)_2(aq) + H_2(g)$
21. Look at the reaction side of each equation in question 20. How many electrons are gained or lost by each atom or ion?

Redox Reactions

Reduction and oxidation reactions are the most common type of chemical reaction. In fact, the term *reduction-oxidation reaction* is used so frequently that it is often shortened to just **redox reaction**.

redox reaction: reduction-oxidation reaction

2.2 Summary

Most metals naturally exist as ores because they tend to lose electrons to form ionic compounds with non-metal ions. A loss of electrons by an atom is called oxidation. The metal ions within an ore can be extracted (removed from the ore) by giving the metal ions electrons. A gain of electrons by an atom is called reduction.

Single replacement reactions can involve oxidation and reduction processes if one reactant gains electrons while another reactant loses electrons. A spectator ion does not lose or gain electrons.

2.2 Questions

Knowledge

1. Define *oxidation*, *reduction*, and *spectator ion*.
2. Explain how single replacement reactions can involve an oxidation and a reduction reaction.
3. Determine whether the following could undergo oxidation, reduction, or both.
    - **a.** an oxygen molecule, $O_2(g)$
    - **b.** an iron(III) ion, $Fe^{3+}(aq)$
    - **c.** an iron(II) ion, $Fe^{2+}(aq)$
    - **d.** an iron atom, $Fe(s)$
    - **e.** a chloride ion, $Cl^-(aq)$
    - **f.** a nitrogen molecule, $N_2(g)$

Applying Concepts

4. When zinc metal is placed into a solution of silver nitrate, silver metal and zinc nitrate are produced.

    $Zn(s) + 2\ AgNO_3(aq) \rightarrow 2\ Ag(s) + Zn(NO_3)_2(aq)$

    - **a.** State the chemical substance that is gaining electrons. Give a reason for your choice.
    - **b.** State the chemical substance that is losing electrons. Give a reason for your choice.
    - **c.** State the chemical substance that is neither gaining nor losing electrons. Give a reason for your choice.
    - **d.** State the atom or ion that is oxidized.
    - **e.** State the atom or ion that is reduced.
    - **f.** State the atom or ion that is a spectator ion.
    - **g.** Determine the number of electrons transferred in the reaction.
    - **h.** If 35.0 mol of zinc react with silver nitrate, how many moles of silver metal will form?
5. When iron metal is exposed to air, it slowly turns into iron(III) oxide. The following equation is a simplification of this process.

    $4\ Fe(s) + 3\ O_2(g) \rightarrow 2\ Fe_2O_3(s)$

    - **a.** State the atom or ion that is oxidized.
    - **b.** State the atom or ion that is reduced.
    - **c.** Determine the number of electrons being transferred.
    - **d.** How many moles of oxygen gas would it take to oxidize 127 mol of iron?
6. Silver atoms react with sulfur atoms found in the air to form silver sulfide (tarnish), $Ag_2S(s)$.

    $4\ Ag(s) + 2\ H_2S(g) + O_2(g) \rightarrow 2\ Ag_2S(s) + 2\ H_2O(l)$

    Identify the chemical substance being oxidized and the chemical substance being reduced. Determine the number of electrons transferred in the reaction.

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Legend: t = top, m = middle, b = bottom, l = left, r = right

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