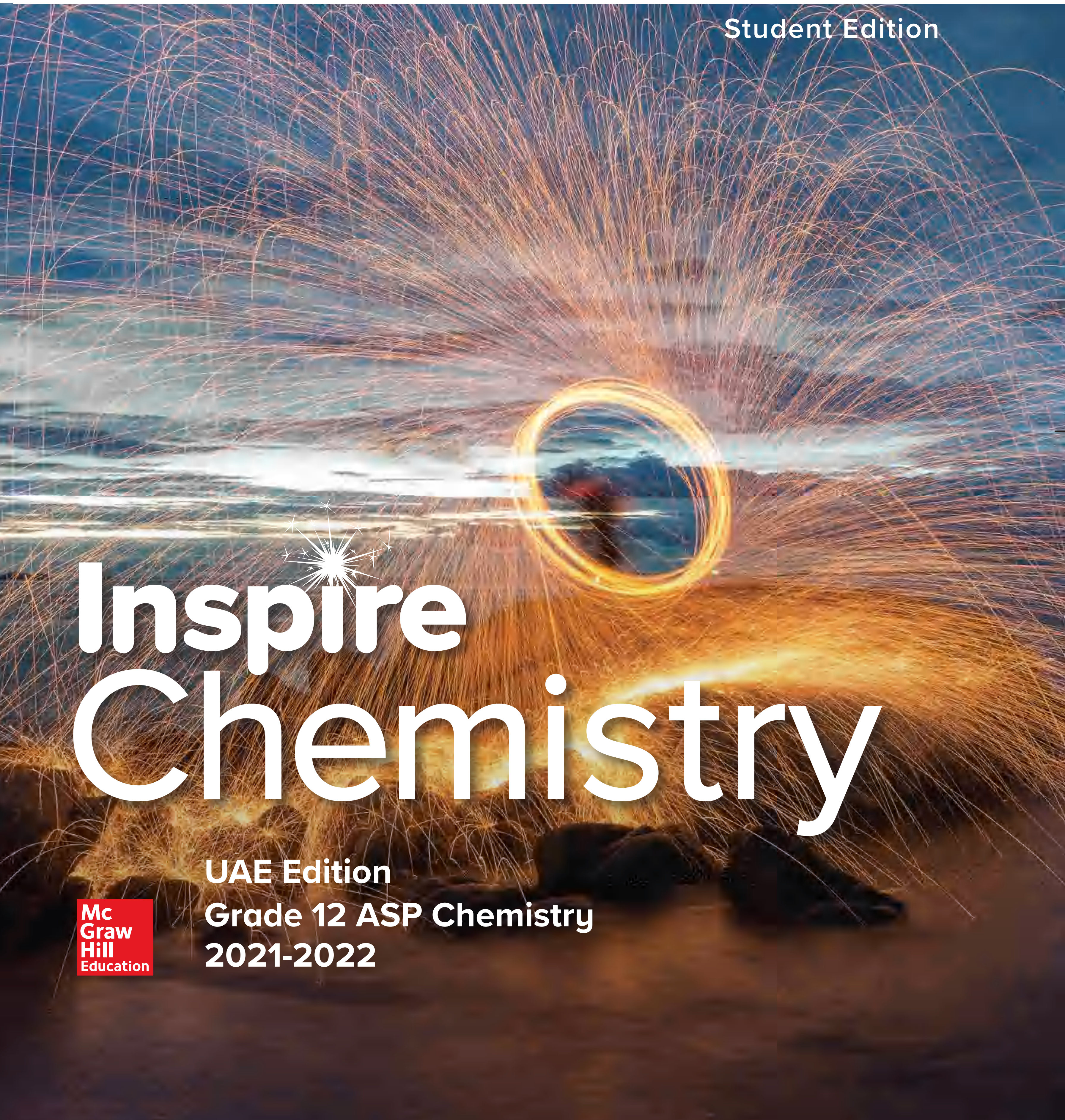
UNITED ARAB EMIRATES
MINISTRY OF EDUCATION

المدرسة الإماراتية



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Contents

REDOX REACTIONS

ENCOUNTER THE PHENOMENON

Why is the water glowing?

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

CER Claim, Evidence, Reasoning

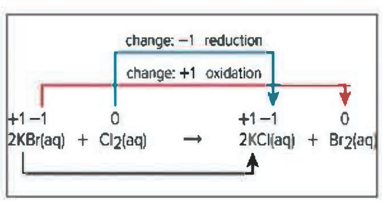
Make Your Claim Use your CER chart to make a claim about why the water is glowing.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.

LESSON 1: Explore & Explain: Defining Oxidation and Reduction



LESSON 1: Explore & Explain: Oxidation Numbers in Redox

LESSON 1
OXIDATION AND REDUCTION

FOCUS QUESTION

What defines oxidation and reduction?

Electron Transfer and Redox Reactions

Previously, you learned that a chemical reaction can usually be classified as one of five types–synthesis, decomposition, combustion, single-replacement, or double-replacement. A defining characteristic of combustion and single-replacement reactions is that they always involve the transfer of electrons from one substance to another, as do many synthesis and decomposition reactions. For example, **Figure 1** shows the burning of magnesium in air, which is a combustion reaction that involves the transfer of electrons.

Complete chemical equation: $2Mg(s) + O_2(g) \rightarrow 2MgO(s)$

Net ionic equation: $2Mg(s) + O_2(g) \rightarrow 2Mg^{2+} + 2O^{2-}$(ions in crystal)

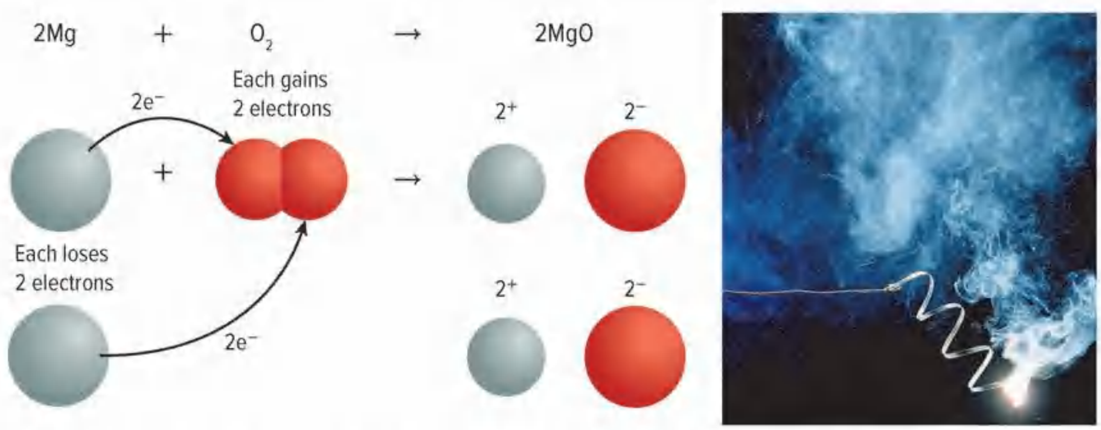


Figure 1 The reaction of magnesium and oxygen involves a transfer of electrons from magnesium to oxygen. Therefore, this reaction is an oxidation-reduction reaction.

Classify *the reaction between magnesium and oxygen.*

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Laboratory: Electron-Losing Tendencies of Metals
Obtain and evaluate information on the effect that electronegativity has on the relative strengths of metals.

Virtual Investigation: Redox Titration
Use chemical properties to analyze data to determine relative concentrations of titrants.

When magnesium reacts with oxygen, each magnesium atom transfers two electrons to each oxygen atom. The two magnesium atoms become magnesium ions (Mg^{2+}), and the two oxygen atoms become oxide ions (O^{2-}). A reaction in which electrons are transferred from one substance to another is called an **oxidation-reduction reaction,** which is also called a **redox reaction.**

Figure 2 shows a single-replacement reaction in which chlorine in an aqueous solution reacts with bromide ions from an aqueous solution of potassium bromide.

Complete chemical equation: $2KBr(aq) + Cl_2(aq) \rightarrow 2KCl(aq) + Br_2(aq)$

Net ionic equation: $2Br^-(aq) + Cl_2(aq) \rightarrow Br_2(aq) + 2Cl^-(aq)$

Note that the chlorine receives electrons from the bromide ions to become chloride ions. When the two bromide ions lose electrons, the two bromine atoms form a covalent bond with each other to produce Br_2 molecules.

Oxidation and reduction

Originally, the word *oxidation* referred only to reactions in which a substance combined with oxygen. Today, **oxidation** is defined as the complete or partial loss of electrons from a reacting substance. Look again at the net ionic equation for the reaction of potassium bromide and chlorine. Bromide ions are oxidized because they lose electrons.

Oxidation: $2Br^- \rightarrow Br_2 + 2e^-$

For oxidation to occur, the electrons lost by the substance that is oxidized must be accepted by atoms or ions of another substance. In other words, there must be an accompanying process that involves the gain of electrons. **Reduction** is the complete or partial gain of electrons by a reacting substance. In this example, the oxidation of bromide ions is accompanied by the reduction of chlorine.

Reduction: $Cl_2 + 2e^- \rightarrow 2Cl^-$

Oxidation and reduction are complementary processes: oxidation cannot occur unless reduction also occurs. It is important to recognize and distinguish between oxidation and reduction. A memory aid to remember the distinction is the phrase **L**oss of **E**lectrons is **O**xidation, and **G**ain of **E**lectrons is **R**eduction, which can be shortened to **LEO GER**.

LEO the lion says **GER** or, for short, **LEO GER**.

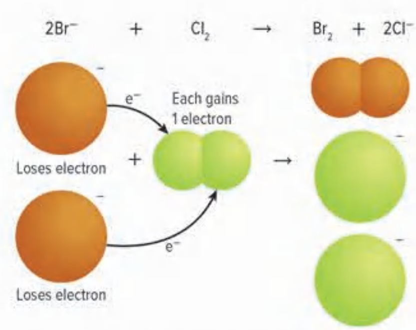


Figure 2 The reaction between aqueous bromide ions and chlorine gas is a redox reaction. Here, electrons are transferred from bromide ions to chlorine.

Oxidation numbers

A number assigned to an atom or ion to indicate its degree of oxidation or reduction is called its **oxidation number.** For example, the oxidation number of an element in an ionic compound is related to the number of electrons lost or gained by an atom of the element when it becomes an ion. The reaction of potassium metal with chlorine vapor, shown in **Figure 3**, is a redox reaction. The equation for the reaction is as follows.

Complete chemical equation: $2K(s) + Cl_2(g) \rightarrow 2KCl(s)$

Net ionic equation: $2K(s) + Cl_2(g) \rightarrow 2K^+(s) + 2Cl^-(s)$

Potassium, a group 1 element whose atoms tend to lose one electron in reactions because of its low electronegativity, is assigned an oxidation number of +1 in KCl. On the other hand, chlorine, a group 17 element whose atoms tend to gain one electron in reactions because of its high electronegativity, is assigned an oxidation number of −1 in KCl. **Table 1** shows oxidation numbers for various elements.

Get It?

Determine Which element is more likely to gain electrons, potassium or chlorine?

Table 1 Various Oxidation Numbers

	+1	+2	+3	−1	−2
Aluminum			X		
Barium		X			
Bromine				X	
Cadmium		X			
Calcium		X			
Cesium	X				
Chlorine				X	
Fluorine				X	
Hydrogen	X			X	
Iodine				X	
Lithium	X				
Magnesium		X			
Oxygen					X
Potassium	X				
Sodium	X				
Silver	X				
Strontium		X			

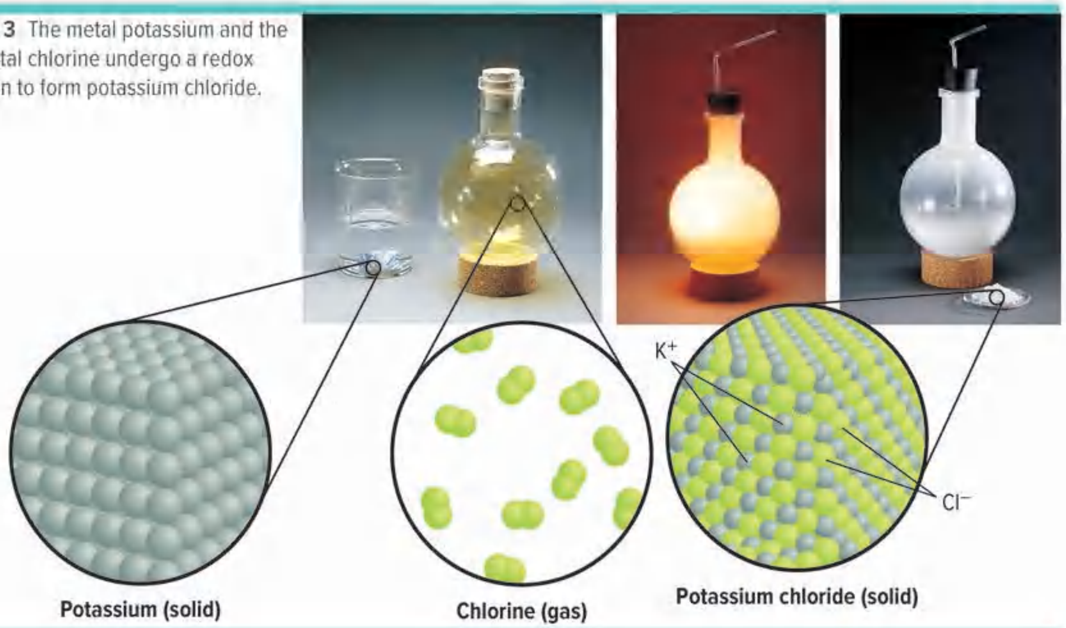


Figure 3 The metal potassium and the nonmetal chlorine undergo a redox reaction to form potassium chloride.

When an atom or ion is reduced, the numerical value of its oxidation number decreases. Conversely, when an atom or ion is oxidized, its oxidation number increases. Oxidation numbers are written with the positive or negative sign before the number (+3, +2), whereas ionic charge is written with the sign after the number (3+, 2+).

Oxidizing and reducing agents

The potassium-chlorine reaction in **Figure 3** can also be described by saying that "potassium is oxidized by chlorine." This description is useful because it clearly identifies both the substance that is oxidized and the substance that does the oxidizing. The substance that oxidizes another substance by accepting its electrons is called an **oxidizing agent.** This term describes the substance that is reduced. The substance that reduces another substance by losing electrons is called a **reducing agent.** A reducing agent supplies electrons to the substance being reduced (gaining electrons). The reducing agent is oxidized because it loses electrons. The reducing agent in the potassium-chlorine reaction is potassium—the substance that is oxidized.

oxidized

$$2K(s) + Cl_2(g) \rightarrow 2KCl(s)$$

reduced

Oxidizing agent: Cl_2

Reducing agent: K

Table 2 Summary of Redox Reactions

Process	e^- X Transfer of electrons Y
Oxidation	
• A reactant loses an electron. • Reducing agent is oxidized. • Oxidation number increases.	• X loses an electron. • X is the reducing agent and becomes oxidized. • The oxidation number of X increases.
Reduction	
• Other reactant gains an electron. • Oxidizing agent is reduced. • Oxidation number decreases.	• Y gains an electron. • Y is the oxidizing agent and becomes reduced. • The oxidation number of Y decreases.

A common application of redox chemistry is to remove tarnish from metal objects. When tarnish remover is applied to the tarnished metal with a soft cloth, the tarnish is easily and quickly removed from the metal. Other oxidizing agents and reducing agents are useful in everyday life. For example, when you add chlorine bleach to your laundry to whiten clothes, you are using an aqueous solution of sodium hypochlorite (NaClO), an oxidizing agent. It oxidizes dyes, stains, and other materials that discolor clothes. **Table 2** summarizes the different ways to describe oxidation-reduction reactions.

Get It?

Describe the changes in oxidation numbers in a redox reaction.

CCC CROSSCUTTING CONCEPTS

Patterns Write a paragraph describing the pattern observed between the oxidizing agent and the reducing agent.

STEM CAREER Connection

Plating Line Technician

Would you like to work in a fast paced environment? Would you like to make products using chemical processes? Then a plating line technician might be the career for you. A plating line technician operates a production line that electroplates a metal onto another metal using redox reactions.

Redox and Electronegativity

The chemistry of oxidation-reduction reactions is not limited to atoms of an element changing to ions or the reverse. Some redox reactions involve changes in molecular substances or polyatomic ions in which atoms are covalently bonded to other atoms. For example, the following equation represents the redox reaction used to manufacture ammonia (NH_3).

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

This process involves neither ions nor any obvious transfer of electrons. The reactants and products are all molecular substances. Yet, it is still a redox reaction in which nitrogen is the oxidizing agent and hydrogen is the reducing agent.

In situations such as the formation of ammonia, where two atoms share electrons, how is it possible to say that one atom lost electrons and was oxidized, while the other atom gained electrons and was reduced? To answer this, you need to know which atom attracts electrons more strongly, or, in other words, which atom is more electronegative.

You might find it helpful to review the discussion of electronegativity trends on the periodic table. **Figure 4** shows that electronegativity increases left to right across a period and generally decreases down a group. Elements with low electronegativity (Groups 1 and 2) are strong reducing agents, and those with high electronegativity (Group 17 and oxygen in Group 16) are strong oxidizing agents.

Hydrogen has an electronegativity of 2.20, and nitrogen has an electronegativity of 3.04. For the purpose of studying oxidation-reduction reactions, the more-electronegative element (in this case nitrogen) is treated as if it had been reduced by gaining electrons from the other element (hydrogen). Conversely, the less-electronegative element (hydrogen) is treated as if it had been oxidized by losing electrons to the other element (nitrogen).

$$\overbrace{N_2(g) + \underbrace{3H_2(g) \rightarrow 2NH_3(g)}_{\text{oxidized (partial loss of } e^-\text{)}}}^{\text{reduced (partial gain of } e^-\text{)}}$$

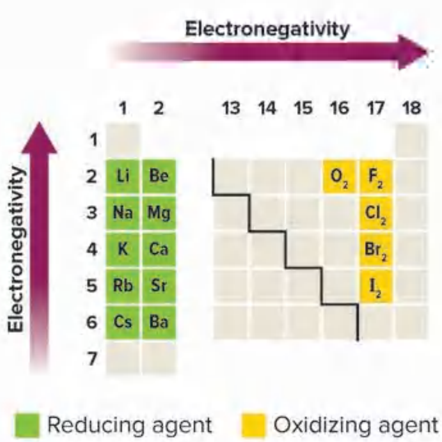


Figure 4 The electronegativity of elements increases from left to right across the periodic table, and it decreases going down a group. Elements with low electronegativity are strong reducing agents, and elements with high electronegativity are strong oxidizing agents.

Predict *which element would be the strongest oxidizing agent. Which is the strongest reducing agent?*

EXAMPLE Problem 1

IDENTIFY OXIDATION-REDUCTION REACTIONS The following equation represents the redox reaction of aluminum and iron.

$2Al + 2Fe^{3+} + 3O^{2-} \rightarrow 2Fe + 2Al^{3+} + 3O^{2-}$

Identify what is oxidized and what is reduced in this reaction. Identify the oxidizing agent and the reducing agent.

1 ANALYZE THE PROBLEM

You are given the reactants and products in the reaction. You must determine the electron transfers that occur. Then, you can apply the definitions of oxidizing agent and reducing agent to answer the question.

2 SOLVE FOR THE UNKNOWN

Identify the oxidation process and the reduction process.

$Al \rightarrow Al^{3+} + 3e^-$ (loss of e^- is oxidation) — The aluminum atom loses three electrons and becomes an aluminum ion.

$Fe^{3+} + 3e^- \rightarrow Fe$ (gain of e^- is reduction) — The iron ion accepts the three electrons lost from aluminum and becomes an iron atom.

Al is oxidized and is therefore the reducing agent. Fe^{3+} is reduced and is therefore the oxidizing agent.

3 EVALUATE THE ANSWER

In this process, aluminum atoms lost electrons and were oxidized, whereas iron ions gained electrons and were reduced. The definitions of oxidation, reduction, oxidizing agent, and reducing agent apply. Note that the ionic charge of oxygen is unchanged in this reaction; therefore, oxygen is not a key factor in this problem.

Real-World Chemistry

Oxidation

RUST When moist air comes in contact with iron, the iron oxidizes. Iron oxide (Fe_2O_3), called rust, is common because iron combines readily with oxygen. Pure iron is uncommon in nature. Steel, a mixture that contains iron, is a commonly used form of iron. Several protective methods, such as plating, painting, and applying an enamel or plastic coating, can inhibit the production of iron oxide.

PRACTICE Problems ADDITIONAL PRACTICE

1. Identify each of the following changes as either oxidation or reduction. Recall that e^- is the symbol for an electron.
   a. $I_2 + 2e^- \rightarrow 2I^-$
   b. $K \rightarrow K^+ + e^-$
   c. $Fe^{2+} \rightarrow Fe^{3+} + e^-$
   d. $Ag^+ + e^- \rightarrow Ag$
2. Identify what is oxidized and what is reduced in the following processes.
   a. $2Br^- + Cl_2 \rightarrow Br_2 + 2Cl^-$
   b. $2Ce + 3Cu^{2+} \rightarrow 3Cu + 2Ce^{3+}$
   c. $2Zn + O_2 \rightarrow 2ZnO$
   d. $2Na + 2H^+ \rightarrow 2Na^+ + H_2$
3. Identify the oxidizing agent and the reducing agent in the following equation. Explain your answer.
   $$Fe(s) + 2Ag^+(aq) \rightarrow Fe^{2+}(aq) + 2Ag(s)$$
4. **CHALLENGE** Identify the oxidizing agent and the reducing agent in each reaction.
   a. $Mg + I_2 \rightarrow MgI_2$
   b. $H_2S + Cl_2 \rightarrow S + 2HCl$

Determining Oxidation Numbers

In order to understand all types of redox reactions, you must have a way to determine the oxidation number ($n_{element}$) of each element involved in a reaction. **Table 3** outlines the rules chemists use to help make this determination easier.

Many elements other than those specified in the rules below, including most of the transition metals, metalloids, and nonmetals, can be found with different oxidation numbers in different compounds. For example, iron has different oxidation numbers, indicated by the different colors shown in **Figure 5**, depending on which minerals are also present.

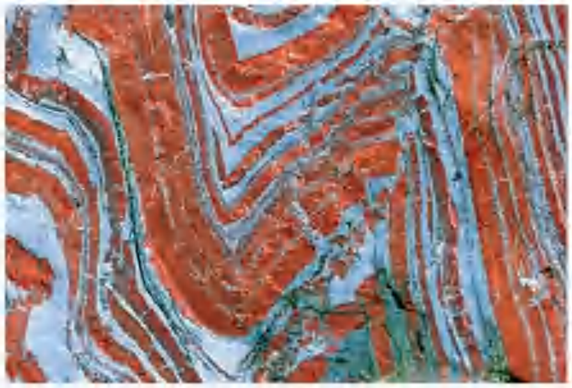


Figure 5 Banded iron—shown in this cross-section of rock—is a result of different oxidation states of iron and the minerals that are present.

Table 3 **Rules for Determining Oxidation Numbers**

Rule	Example	$n_{element}$
1. The oxidation number of an atom of an uncombined element is zero.	Na, O_2, Cl_2, H_2	0
2. The oxidation number of a monatomic ion is equal to the charge of the ion.	Ca^{2+}	+2
	Br^-	−1
3. The oxidation number of the more electronegative atom in a molecule or a complex ion is the same as the charge it would have if it were an ion.	N in NH_3	−3
	O in NO	−2
4. The oxidation number of the most electronegative element, fluorine, is always −1 when it is bonded to another element.	F in LiF	−1
5. The oxidation number of oxygen in compounds is always −2 except in peroxides, such as hydrogen peroxide (H_2O_2), where it is −1. When it is bonded to fluorine, the only element more electronegative than oxygen, the oxidation number of oxygen is positive.	O in NO_2	−2
	O in H_2O_2	−1
6. The oxidation number of hydrogen in most of its compounds is +1, except in metal hydrides; then, the oxidation number is −1.	H in NaH	−1
7. The oxidation numbers of group 1 and 2 metals and aluminum are positive and equal to their number of valence electrons.	K	+1
	Ca	+2
	Al	+3
8. The sum of the oxidation numbers in a neutral compound is zero.	$CaBr_2$	$(+2) + 2(-1) = 0$
9. The sum of the oxidation numbers of the atoms in a polyatomic ion is equal to the charge of the ion.	SO_3^{2-}	$(+4) + 3(-2) = -2$

EXAMPLE Problem 2

DETERMINE OXIDATION NUMBERS Use the rules for determining oxidation numbers to find the oxidation number of each element in potassium chlorate ($KClO_3$) and in a sulfite ion (SO_3^{2-}).

1 ANALYZE THE PROBLEM

In the rules for determining oxidation numbers, you are given the oxidation numbers of oxygen and potassium. You are also given the overall charge of the compound or ion. Using this information and applying the rules, determine the oxidation numbers of chlorine and sulfur. (Let $n_{element}$ equal the oxidation number of the element in question.)

Known	Unknown
$KClO_3$	$n_{Cl} = ?$
SO_3^{2-}	$n_S = ?$
$n_O = -2$	
$n_K = +1$	

2 SOLVE FOR THE UNKNOWN

Assign the known oxidation numbers to their elements, set the sum of all oxidation numbers to zero or to the ion charge, and solve for the unknown oxidation number.

$(n_K) + (n_{Cl}) + 3(n_O) = 0$ The sum of the oxidation numbers in a neutral compound is zero.

$(+1) + (n_{Cl}) + 3(-2) = 0$ For group 1 metals, $n_{element} = +1$. Substitute $n_K = +1$, $n_O = -2$.

$1 + n_{Cl} + (-6) = 0$

$n_{Cl} = +5$ Solve for n_{Cl}.

$(n_S) + 3(n_O) = -2$ The sum of the oxidation numbers in a polyatomic ion equals the charge on the ion. Substitute $n_O = -2$

$(n_S) + 3(-2) = -2$

$(n_S) + (-6) = -2$

$n_S = +4$ Solve for n_S.

3 EVALUATE THE ANSWER

The rules for determining oxidation numbers have been correctly applied. All of the oxidation numbers in each substance add up to the proper value.

PRACTICE Problems ADDITIONAL PRACTICE

5. Determine the oxidation number of the boldface element in the following formulas for compounds.
   a. Na**Cl**O_4 **b.** Al**P**O_4 **c.** H**N**O_2
6. Determine the oxidation number of the boldface element in the following formulas for ions.
   a. **N**H_4^+ **b.** **As**O_4^{3-} **c.** **Cr**O_4^{2-}
7. Determine the oxidation number of nitrogen in each of these molecules.
   a. NH_3 **b.** KCN **c.** N_2H_4
8. **CHALLENGE** Determine the net change of oxidation number of each of the elements in these redox equations.
   a. $C + O_2 \rightarrow CO_2$
   b. $Cl_2 + ZnI_2 \rightarrow ZnCl_2 + I_2$
   c. $CdO + CO \rightarrow Cd + CO_2$

Oxidation Numbers in Redox Reactions

Recall the replacement reaction of bromine in aqueous potassium bromide (KBr) by chlorine (Cl_2). Assign numbers, using **Table 1**, to all elements in the balanced equation. Then review the changes, as shown in the equation below. The oxidation number of bromine changed from −1 to 0, an increase of 1 while the oxidation number of chlorine changed from 0 to −1, a decrease of 1. Therefore, chlorine is reduced, and bromine is oxidized.

change: −1 reduction

change: +1 oxidation

$$\overset{+1-1}{2KBr}(aq) + \overset{0}{Cl_2}(aq) \rightarrow \overset{+1-1}{2KCl}(aq) + \overset{0}{Br_2}(aq)$$

no change in oxidation number

Check Your Progress

Summary

- Oxidation-reduction reactions involve the transfer of electrons from one atom to another.
- When an atom or ion is reduced, its oxidation number decreases. When an atom or ion is oxidized, its oxidation number increases.
- In oxidation-reduction reactions involving molecular compounds (and polyatomic ions with covalent bonds), the more-electronegative atoms are treated as if they are reduced. The less-electronegative atoms are treated as if they are oxidized.

Demonstrate Understanding

9. **Explain** why oxidation and reduction must always occur together.
10. **Describe** the roles of oxidizing agents and reducing agents in a redox reaction. How is each changed in the reaction?
11. **Write** the equation for the reaction of iron metal with hydrobromic acid to form aqueous iron(III) bromide and hydrogen gas. Determine the change in oxidation number for the element that is reduced and the element that is oxidized.
12. **Determine** the oxidation number of the boldface element in these compounds.
    a. $H\mathbf{N}O_3$
    b. $Ca_3\mathbf{N}_2$
    c. $\mathbf{Sb}_2O_5$
    d. $Cu\mathbf{W}O_4$
13. **Determine** the oxidation number of the boldface element in these ions.
    a. $\mathbf{I}O_4^-$
    b. $\mathbf{Mn}O_4^-$
    c. $\mathbf{B}_4O_7^{2-}$
    d. $\mathbf{N}H_2^-$
14. **Make and Use Graphs** Alkali metals are strong reducing agents. Make a graph showing how the reducing abilities of the alkali metals increase or decrease as you move down the family from sodium to francium.

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LESSON 2

BALANCING REDOX EQUATIONS

FOCUS QUESTION

How do you balance redox equations?

The Oxidation-Number Method

Chemical equations must be balanced to show the correct quantities of reactants and products. **Figure 6** shows the reaction that occurs when copper metal is placed in concentrated nitric acid. The brown gas that is produced is nitrogen dioxide (NO_2), from the reduction of nitrate ions (NO_3^-), and the blue solution is the result of the oxidation of copper (Cu) to copper(II) ions (Cu^{2+}). Here is the unbalanced equation for this reaction:

$$Cu(s) + HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + NO_2(g) + H_2O(l)$$

Note that oxygen appears in only one reactant, HNO_3, but it appears in all three products. Nitrogen also appears in HNO_3 and in two of the products. Redox equations such as this one, in which the same element appears in several reactants and products, can be difficult to balance.

As you have read, when an atom or ion loses electrons, its oxidation number increases; when an atom or ion gains electrons, its oxidation number decreases. The number of electrons transferred from atoms or ions must equal the number of electrons accepted by other atoms or ions. Therefore, the total increase in oxidation numbers (oxidation) must equal the total decrease in oxidation numbers (reduction) of the atoms or ions involved in the reaction.

These principles are the basis for an equation-balancing technique called the **oxidation number method.** The Example Problem on the next page shows how to use this method to balance the equation for the reaction shown in **Figure 6**.

Figure 6 The redox reaction between copper and nitric acid can be difficult to balance because elements appear more than once on each side of the equation.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

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INVESTIGATE

GO ONLINE to find these activities and more resources.

ChemLAB: Identify the Damaging Dumper

Carry out an investigation to determine patterns in pollutants that may have been spilled.

Laboratory: Determining Oxidation Numbers

Analyze and interpret data from reduction potentials and gravimetric analysis to find patterns in oxidation numbers in all types of substances present.

EXAMPLE Problem 3

THE OXIDATION-NUMBER METHOD Balance the following redox equation.

$$Cu + HNO_3 \rightarrow Cu(NO_3)_2 + NO_2 + H_2O$$

1 ANALYZE THE PROBLEM

Use the rules for determining oxidation numbers. The increase in oxidation number of the oxidized atoms or ions must equal the decrease in oxidation number of the reduced atoms or ions. Adjust the coefficients to balance the equation.

2 SOLVE FOR THE UNKNOWN

Assign oxidation numbers to all elements in the equation.

$$\overset{0}{Cu} + \overset{+1}{H}\overset{+5}{N}\overset{-2}{O_3} \rightarrow \overset{+2}{Cu}(\overset{+5}{N}\overset{-2}{O_3})_2 + \overset{+4}{N}\overset{-2}{O_2} + \overset{+1}{H_2}\overset{-2}{O}$$

The oxidation number of copper increases from 0 to +2. The oxidation number of nitrogen decreases from +5 to +4.

Identify which atoms or ions are oxidized, which are reduced, and which do not change.

Cu is oxidized.
N is reduced.
H and O do not change. N does not change in the nitrate ion (NO_3^-).

Determine the changes in oxidation number for the atoms or ions that are oxidized and for the atoms or ions that are reduced.

Changes in oxidation number:
Oxidized: Cu +2
Reduced: N −1

Copper loses electrons. It is oxidized.
Nitrogen gains electrons. It is reduced.

Make the changes in oxidation numbers equal in magnitude by adjusting coefficients in the equation.

$$Cu + 2HNO_3 \rightarrow Cu(NO_3)_2 + 2NO_2 + H_2O$$
$$2(-1) = -2$$

Because the change in oxidation number for N is −1, you must add a coefficient of 2 to balance. This coefficient applies to both HNO_3 and NO_2.

Use the conventional method to balance the remainder of the equation.

$$Cu + 2HNO_3 \rightarrow Cu(NO_3)_2 + 2NO_2 + H_2O$$
$$Cu + 4HNO_3 \rightarrow Cu(NO_3)_2 + 2NO_2 + H_2O$$

The coefficient of HNO_3 must be increased from 2 to 4 to balance the four nitrogen atoms in the products.

$$Cu(s) + 4HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2NO_2(g) + 2H_2O(l)$$

Add a coefficient of 2 to H_2O to balance the four hydrogen atoms on the left.

3 EVALUATE THE ANSWER

The number of atoms of each element is equal on both sides of the equation. No subscripts have been changed.

PRACTICE Problems

ADDITIONAL PRACTICE

Use the oxidation-number method to balance these redox equations.

15. $HCl + HNO_3 \rightarrow HOCl + NO + H_2O$

16. $SnCl_4 + Fe \rightarrow SnCl_2 + FeCl_3$

17. $NH_3(g) + NO_2(g) \rightarrow N_2(g) + H_2O(l)$

18. CHALLENGE $SO_2 + Br_2 + H_2O \rightarrow HBr + H_2SO_4$

Table 4 **The Oxidation-Number Method**

1. Assign oxidation numbers to all chemical elements in the equation.
2. Identify the atoms or ions that are oxidized and reduced.
3. Determine the change in oxidation number for the atoms or ions that are oxidized and for the atoms or ions that are reduced.
4. Make the change in oxidation numbers equal in magnitude by adjusting coefficients in the equation.
5. If necessary, use the conventional method to balance the remainder of the equation.

Table 4 summarizes the oxidation-number method for balancing equations in redox reactions. Compare the steps in **Table 4** to the previous Example Problem to see how each step is applied to solve a problem.

Balancing Net Ionic Redox Equations

Sometimes, chemists prefer to express redox reactions in the simplest possible terms—as an equation showing only the oxidation and reduction processes. Refer again to the balanced equation for the oxidation of copper by nitric acid.

$$Cu(s) + 4HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2NO_2(g) + 2H_2O(l)$$

Note that the reaction takes place in aqueous solution, so HNO_3, which is a strong acid, will be ionized. Likewise, copper(II) nitrate ($Cu(NO_3)_2$) will be dissociated into ions. Therefore, the equation can also be written in ionic form.

$$Cu(s) + 4H^+(aq) + 4NO_3^-(aq) \rightarrow Cu^{2+}(aq) + 2NO_3^-(aq) + 2NO_2(g) + 2H_2O(l)$$

There are four nitrate ions among the reactants, but only two of them undergo change to form two nitrogen dioxide molecules. The other two nitrate ions are only spectator ions and can be eliminated from the equation. To simplify when writing redox equations in ionic form, chemists usually indicate hydrogen ions by H^+ with the understanding that they exist in hydrated form as hydronium ions (H_3O^+). The equation can then be rewritten showing only the substances that undergo change.

$$Cu(s) + 4H^+(aq) + 2NO_3^-(aq) \rightarrow Cu^{2+}(aq) + 2NO_2(g) + 2H_2O(l)$$

Now look at the equation in unbalanced form.

$$Cu(s) + H^+(aq) + NO_3^-(aq) \rightarrow Cu^{2+}(aq) + NO_2(g) + H_2O(l)$$

You might also see this same reaction expressed in a way that shows only the substances that are oxidized and reduced.

$$Cu(s) + NO_3^-(aq) \rightarrow Cu^{2+}(aq) + NO_2(g) \text{ (in acidic solution)}$$

Note that the hydrogen ion and the water molecule are eliminated because neither is oxidized or reduced. In acidic solution, hydrogen ions (H^+) and water molecules are free to participate in redox reactions as either reactants or products. Some redox reactions can occur only in basic solution. When you balance equations for these reactions, you can add hydroxide ions (OH^-) and water molecules to either side of the equation.

EXAMPLE Problem 4

BALANCE A NET IONIC REDOX EQUATION Balance the following redox equation.

$$ClO_4^-(aq) + Br^-(aq) \rightarrow Cl^-(aq) + Br_2(g) \text{ (in acidic solution)}$$

1 ANALYZE THE PROBLEM

Use the rules for determining oxidation numbers. The increase in oxidation number of the oxidized atoms or ions must equal the decrease in oxidation number of the reduced atoms or ions. The reaction takes place under acidic conditions. Adjust the coefficients to balance the equation.

2 SOLVE FOR THE UNKNOWN

Assign oxidation numbers to all elements in the equation.

$$\overset{+7\,-2}{ClO_4^-}(aq) + \overset{-1}{Br^-}(aq) \rightarrow \overset{-1}{Cl^-}(aq) + \overset{0}{Br_2}(g) \text{ (in acidic solution)}$$

Use the rules in Table 3.

Identify which atoms or ions are oxidized and which are reduced.

Br is oxidized.
Cl is reduced.

The oxidation number of bromine increases from −1 to 0. The oxidation number of chlorine decreases from +7 to −1.

Determine the changes in oxidation numbers for the atoms or ions that are oxidized and reduced.

Changes in oxidation number:
Br +1
Cl −8

Bromine loses electrons. It is oxidized.
Chlorine gains electrons. It is reduced.

Make the changes in oxidation numbers equal in magnitude by adjusting coefficients in the equation.

$$ClO_4^-(aq) + 8Br^-(aq) \rightarrow Cl^-(aq) + 4Br_2(g) \text{ (in acidic solution)}$$

Because the change in oxidation number of Br is +1, you must add the coefficient 8 to balance the equation. $4Br_2$ represents 8 Br atoms to balance the $8Br^-$ on the left side.

Add enough hydrogen ions and water molecules to the equation to balance the oxygen atoms on both sides.

$$ClO_4^-(aq) + 8Br^-(aq) + 8H^+(aq) \rightarrow Cl^-(aq) + 4Br_2(g) + 4H_2O(l)$$

Because you know the reaction takes place in acid solution, you can add H^+ ions on the left side of the equation.

3 EVALUATE THE ANSWER

The number of atoms of each element is equal on both sides of the equation.
As with any ionic equation, the net charge on the right equals the net charge on the left.
No subscripts have been changed.

PRACTICE Problems

ADDITIONAL PRACTICE

Use the oxidation-number method to balance these redox equations.

19. $H_2S(g) + NO_3^-(aq) \rightarrow S(s) + NO(g)$ (in acidic solution)

20. $Cr_2O_7^{2-}(aq) + I^-(aq) \rightarrow Cr^{3+}(aq) + I_2(s)$ (in acidic solution)

21. $Zn + NO_3^- \rightarrow Zn^{2+} + NO_2$ (in acidic solution)

22. CHALLENGE $I^-(aq) + MnO_4^-(aq) \rightarrow I_2(s) + MnO_2(s)$ (in basic solution)

BIOLOGY Connection What do many deep-sea fishes and fireflies have in common with the sea sparkle, *Noctiluca scintillans?* These and other organisms emit light. Bioluminescence is the conversion of potential energy in chemical bonds into light during a redox reaction. Depending on the species, bioluminescence is produced by different chemicals and by different means. In fireflies, like the one shown in **Figure 7**, light results from the oxidation of the molecule luciferin.

Figure 7 Organisms use bioluminescence for different purposes, such as attracting a mate and defending against predators.

Get It?
Recognize and identify the energy transformation that occurs in bioluminescence.

Balancing Redox Equations Using Half-Reactions

In chemistry, a **species** is any kind of chemical unit involved in a process. In the equilibrium equation $NH_3 + H_2O \leftrightarrows NH_4^+ + OH^-$, there are four species: the two molecules, NH_3 and H_2O, and the two ions, NH_4^+ and OH^-. Oxidation-reduction reactions occur whenever a species that can give up electrons (reducing agent) comes in contact with another species that can accept them (oxidizing agent).

For example, iron can reduce many species that are oxidizing agents, including chlorine.

$$2Fe + 3Cl_2 \rightarrow 2FeCl_3$$

In this reaction, each iron atom is oxidized by losing three electrons to become an Fe^{3+} ion. At the same time, each chlorine atom in Cl_2 is reduced by accepting one electron to become a Cl^- ion.

$$\text{Oxidation: } Fe \rightarrow Fe^{3+} + 3e^-$$

$$\text{Reduction: } Cl_2 + 2e^- \rightarrow 2Cl^-$$

Equations such as these represent half-reactions. A **half-reaction** is one of the two parts of a redox reaction—the oxidation half or the reduction half. **Table 5** shows several more reduction half-reactions that involve the oxidation of Fe to Fe^{3+}.

Table 5 **Redox Reactions that Oxidize Iron**

Overall Reaction (Unbalanced)	Oxidation Half-Reaction	Reduction Half-Reaction
$Fe + O_2 \rightarrow Fe_2O_3$	$Fe \rightarrow Fe^{3+} + 3e^-$	$O_2 + 4e^- \rightarrow 2O^{2-}$
$Fe + F_2 \rightarrow FeF_3$		$F_2 + 2e^- \rightarrow 2F^-$
$Fe + HBr \rightarrow H_2 + FeBr_3$		$2H^+ + 2e^- \rightarrow H_2$
$Fe + AgNO_3 \rightarrow Ag + Fe(NO_3)_3$		$Ag^+ + e^- \rightarrow Ag$
$Fe + CuSO_4 \rightarrow Cu + Fe_2(SO_4)_3$		$Cu^{2+} + 2e^- \rightarrow Cu$

Figure 8 As a result of this redox reaction between iron and copper(II) sulfate solution, solid copper metal is deposited on the iron. To balance the chemical equation for this reaction, you could use half-reactions.

Half-reactions can be used to balance redox equations. For example, here is the unbalanced equation for the reaction shown in **Figure 8**.

$$Fe(s) + CuSO_4(aq) \rightarrow Cu(s) + Fe_2(SO_4)_3(aq)$$

Iron atoms are oxidized as they lose electrons to copper(II) ions. **Table 6** shows the steps for balancing this and other redox equations by using half-reactions.

Table 6 **The Half-Reaction Method**

1. Write the unbalanced, net ionic equation for the reaction, omitting spectator ions. $Fe + Cu^{2+} + SO_4^{2-} \rightarrow Cu + 2Fe^{3+} + 3SO_4^{2-}$ $Fe + Cu^{2+} \rightarrow Cu + 2Fe^{3+}$
2. Write separate, incomplete equations for the oxidation and reduction half-reactions, including oxidation numbers. $\overset{0}{Fe} \rightarrow 2\overset{+3}{Fe^{3+}}$ (oxidation) $\overset{+2}{Cu^{2+}} \rightarrow \overset{0}{Cu}$ (reduction)
3. Balance the atoms in the half-reactions. Balance the charges in each half-reaction by adding electrons as reactants or products. $2Fe \rightarrow 2Fe^{3+} + 6e^-$ $Cu^{2+} + 2e^- \rightarrow Cu$
4. Adjust the coefficients so that the number of electrons lost in oxidation equals the number of electrons gained in reduction. $2Fe \rightarrow 2Fe^{3+} + 6e^-$ $3Cu^{2+} + 6e^- \rightarrow 3Cu$
5. Add the half-reactions and cancel or reduce like terms on both sides of the equation. $2Fe + 3Cu^{2+} \rightarrow 3Cu + 2Fe^{3+}$
6. Return spectator ions, if desired. Restore state descriptions. $2Fe(s) + 3CuSO_4(aq) \rightarrow 3Cu(s) + Fe_2(SO_4)_3(aq)$

SCIENCE USAGE v. COMMON USAGE

species

Science usage: in chemistry, any kind of representative particle involved in a process

In a synthesis reaction, two distinct species combine to form a single product.

Common usage: a class of individuals having some common characteristics or qualities; a distinct sort or kind

Humans and chimpanzees are two different species.

ACADEMIC VOCABULARY

method

a way of doing something

Students study for an exam using different methods.

EXAMPLE Problem 5

BALANCE A REDOX EQUATION BY USING HALF-REACTIONS Balance the redox equation for the reaction below using half-reactions.

$$KMnO_4(aq) + SnCl_2(aq) + HCl(aq) \rightarrow MnCl_2(aq) + SnCl_4(aq) + H_2O(l) + KCl(aq)$$

1 ANALYZE THE PROBLEM

The reaction takes place in acidic solution. Use the rules for determining oxidation numbers and the steps for balancing by half-reactions to balance the equation for the reaction.

2 SOLVE FOR THE UNKNOWN

Write the unbalanced, net ionic equation for the reaction.

$MnO_4^- + Sn^{2+} \rightarrow Mn^{2+} + Sn^{4+}$

Eliminate coefficients, spectator ions, and state symbols.

Write incomplete equations for the oxidation and reduction half-reactions, including oxidation numbers.

$\overset{+2}{Sn^{2+}} \rightarrow \overset{+4}{Sn^{4+}}$ (oxidation)

$\overset{+7}{MnO_4^-} \rightarrow \overset{+2}{Mn^{2+}}$ (reduction)

Use the rules in Table 3 and Table 6.

Balance the atoms and charges in the half-reactions.

$Sn^{2+} \rightarrow Sn^{4+} + 2e^-$ (oxidation)

$5e^- + 8H^+ + MnO_4^- \rightarrow Mn^{2+} + 4H_2O$ (reduction)

In an acid solution, H_2O molecules are available in abundance and can be used to balance oxygen atoms in the half-reactions; H^+ ions are readily available and can be used to balance the charge.

Adjust the coefficients so that the number of electrons lost in oxidation equals the number of electrons gained in reduction.

$5Sn^{2+} \rightarrow 5Sn^{4+} + 10e^-$ (oxidation)

$10e^- + 16H^+ + 2MnO_4^- \rightarrow 2Mn^{2+} + 8H_2O$ (reduction)

The least common multiple of 2 and 5 is 10. Cross-multiplying gives the balanced oxidation and reduction half-reactions.

Add the balanced half-reactions and simplify by canceling or reducing like terms on both sides of the equation.

$5Sn^{2+} + 10e^- + 16H^+ + 2MnO_4^- \rightarrow 5Sn^{4+} + 10e^- + 2Mn^{2+} + 8H_2O$

$5Sn^{2+} + 16H^+ + 2MnO_4^- \rightarrow 5Sn^{4+} + 2Mn^{2+} + 8H_2O$

Restore state descriptions and return spectator ions (K^+ and Cl^-).

$5SnCl_2(aq) + 16HCl(aq) + 2KMnO_4(aq) \rightarrow$
$5SnCl_4(aq) + 2MnCl_2(aq) + 8H_2O(l) + 2KCl(aq)$

Add K^+ ions to the two MnO_4^- ions on the left and add two K^+ ions on the right. Add Cl^- ions to the Sn^{2+} and H^+ ions on the left and to the Sn^{4+}, Mn^{2+}, and K^+ ions on the right.

3 EVALUATE THE ANSWER

A review of the balanced equation indicates that the number of atoms of each element is equal on both sides of the equation. No subscripts have been changed.

PRACTICE Problems ADDITIONAL PRACTICE

Use the half-reaction method to balance the redox equations. Begin by writing the oxidation and reduction half-reactions. Leave the balanced equation in ionic form.

23. $Cr_2O_7^{2-}(aq) + I^-(aq) \rightarrow Cr^{3+}(aq) + I_2(s)$ (in acidic solution)

24. $Mn^{2+}(aq) + BiO_3^-(aq) \rightarrow MnO_4^-(aq) + Bi^{2+}(aq)$ (in acidic solution)

25. CHALLENGE $N_2O(g) + ClO^-(aq) \rightarrow NO_2^-(aq) + Cl^-(aq)$ (in basic solution)

PROBLEM-SOLVING STRATEGY

Balancing Redox Equations

Determine which species is oxidized

Do the oxidized and reduced species appear more than once on either side of the equation, or does the reaction occur in an acidic or basic solution?

No → Use the oxidation-number method of balancing redox equations.

Yes → Use the half-reaction method of balancing redox equations.

Apply the Strategy

Balance the following equation using this flowchart.

$P_4(s) + H_2O(l) \rightarrow PH_3(g) + H_2PO_2(aq)$

Check Your Progress

Summary

- The oxidation-number method is based on the number of electrons transferred from atoms or ions equaling the number of electrons accepted by other atoms or ions.
- To balance equations for reactions in an acidic (or basic) solution, add hydrogen (or hydroxide) ions and water molecules.
- A half-reaction is one of the two parts of a redox reaction.

Demonstrate Understanding

26. **Characterize** redox reactions by explaining how changes in oxidation numbers are related to the electrons transferred in a redox reaction. How are the changes related to the processes of oxidation and reduction?
27. **Describe** why it is important to know the conditions under which an aqueous oxidation-reduction reaction takes place in order to balance the ionic equation for the reaction.
28. **Explain** the steps of the oxidation-number method of balancing equations.
29. **State** what an oxidation half-reaction shows. What does a reduction half-reaction show?
30. **Write** the oxidation and reduction half-reactions for the redox equation $Pd^{2+} + Pb \rightarrow Pd + Pb^{2+}$.

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NATURE OF SCIENCE

Better Eating Through Chemistry

Everyone loves the sight and smell of freshly baked bread. Did you know that a chemical reaction called the Maillard reaction is the cause of bread's pleasant effects on our senses? This reaction is what gives foods their distinctive tastes and colors. The Maillard reaction is actually many reactions that occur in different patterns, producing many different chemical compounds. The reactions include the oxidation-reduction, or redox, reaction that occurs when people cook food.

The Maillard reaction gives breads and other baked goods their golden-brown crust.

The "browning" reaction

The Maillard reaction, which occurs between simple sugars and proteins, was first identified in 1912 by French physician and biochemist Louis-Camille Maillard. It is also called the "browning" reaction because of the color produced in foods—such as meats, coffee, chocolate, and potato chips—that have undergone the reaction.

High temperatures and low-moisture conditions produce the Maillard reaction most rapidly, including the cooking techniques of browning, frying, baking, grilling, and roasting. However, the Maillard reaction also occurs slowly to some foods, in the absence of a heat source. Slow Maillard reactions that occur at room temperature give some honeys their dark color.

The Maillard reaction is still not well understood and scientists continue to study it. They have found that the reaction produces negative, as well as positive, results in foods. It causes the breakdown of dry foods such as flour, as well as the loss of viability in seeds. The reaction may also form the carcinogens that are found in burned meat.

Scientists have discovered that the Maillard reaction is found in human beings. The reaction has been linked to the aging process in humans and to the development of human diseases.

PLAN AND CONDUCT AN INVESTIGATION

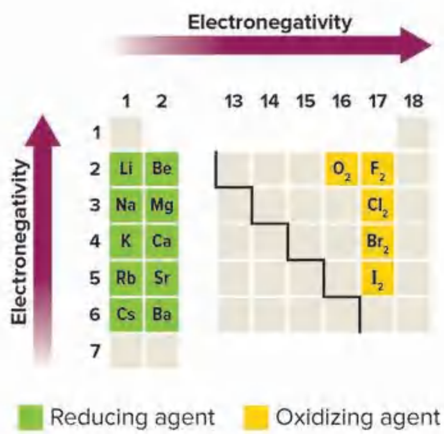
Work with a partner to write a lab procedure for observing the effects of the Maillard reaction. If possible, identify a redox reaction that occurs. Use your data to draw conclusions and present them to your class.

STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 OXIDATION AND REDUCTION

- Oxidation-reduction reactions involve the complete or partial transfer of electrons from one substance to another.
- When an atom or ion is reduced, its oxidation number is lowered. When an atom or ion is oxidized, its oxidation number is raised.
- In oxidation-reduction reactions involving molecular compounds (and polyatomic ions with covalent bonds), the more-electronegative atoms are treated as if they are reduced. The less-electronegative atoms are treated as if they are oxidized.



- oxidation-reduction reaction
- redox reaction
- oxidation
- reduction
- oxidation number
- oxidizing agent
- reducing agent

Lesson 2 BALANCING REDOX EQUATIONS

- Redox equations in which the same element appears in several reactants and products can be difficult to balance using the conventional method.
- The oxidation-number method is based on the number of electrons transferred from atoms or ions equaling the number of electrons accepted by other atoms or ions.
- To balance equations for reactions in an acidic solution, add hydrogen ions and water molecules.
- To balance equations for reactions in a basic solution, add hydroxide ions and water molecules.
- A half-reaction is one of the two parts of a redox reaction.

- oxidation-number method
- species
- half-reaction

THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

Why is the water glowing?

CER Claim, Evidence, Reasoning

Explain Your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

Based on Real Data*

SEP Data Analysis Lab

How does redox lift a space shuttle?

The space shuttle gained nearly 72% of its lift from two solid rocket boosters (SRBs) during the first two minutes of launch. Each SRB contained approximately 499,000 kg of propellant mixture. The table gives the composition of the propellant mixture.

Data and Observations

SRB Propellant Mixture

Component	Percent Composition
Ammonium perchlorate	69.6
Aluminum	16
Binder	12.04
Curing agent	1.96
Catalyst	0.4

*Data obtained from: Dumoulin, Jim. "Solid Rocket Boosters." *NSTS Shuttle Reference Manual*. 1988

CER Analyze and Interpret Data

1. **Balance an equation** Use the oxidation-number method to balance the chemical equation for the SRB reaction.

   $NH_4ClO_4(s) + Al(s) \rightarrow$

   $Al_2O_3(g) + HCl(g) + N_2(g) + H_2O(g)$
2. **Claim** Which elements are reduced and which are oxidized?
3. **Evidence, Reasoning** What are the benefits of using SRBs for the first two minutes of launch?
4. **Calculate** How many moles of water vapor are produced by one SRB?

ELECTROCHEMISTRY

ENCOUNTER THE PHENOMENON

Where do cameras get their power?

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

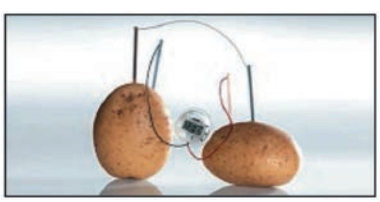
CER Claim, Evidence, Reasoning

Make Your Claim Use your CER chart to make a claim about where cameras get their power.

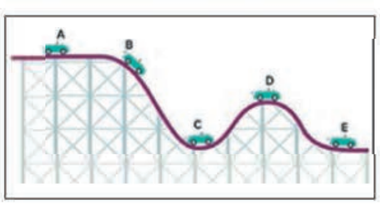
Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.



LESSON 1: Explore & Explain: Redox in Electrochemistry



LESSON 1: Explore & Explain: Voltaic Cells and Energy

LESSON 1

VOLTAIC CELLS

FOCUS QUESTION

How do voltaic cells harness energy from chemical reactions?

Redox in Electrochemistry

Electrochemistry is the study of the redox processes by which chemical energy is converted to electrical energy and vice versa. Recall that all redox reactions involve a transfer of electrons from the species that is oxidized to the species that is reduced. **Figure 1** and **Figure 2,** on the next page, illustrate the simple redox reaction in which zinc atoms are oxidized to form zinc (Zn^{2+}) ions. The two electrons donated from each zinc atom are accepted by a copper (Cu^{2+}) ion, which becomes an atom of copper metal.

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

Figure 1 In **a**, zinc metal is immersed in 1*M* zinc sulfate solution, and copper metal in 1*M* copper(II) sulfate. In **b**, a wire joining the zinc and copper strips provides a pathway for the flow of electrons, but the pathway is not complete. Electron transfer is still not possible.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Virtual Investigation: Electrochemical Cells

Plan and carry out an investigation to determine the standard electrochemical cell potential proportion of one cell and of several cells linked together.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Half-reactions

Two half-reactions make up this redox process:

$$Zn \rightarrow Zn^{2+} + 2e^- \text{ (oxidation half-reaction: electrons lost)}$$
$$Cu^{2+} + 2e^- \rightarrow Cu \text{ (reduction half-reaction: electrons gained)}$$

What do you think would happen if you separated the oxidation half-reaction from the reduction half-reaction? Can a redox reaction occur? Consider **Figure 1a**, in which a zinc strip is immersed in a solution of zinc sulfate and a copper strip is immersed in a solution of copper(II) sulfate.

Two problems prevent a redox reaction from occurring. First, there is no way for zinc atoms to transfer electrons to copper(II) ions. This problem can be solved by connecting the zinc and copper strips with a metal wire, as shown in **Figure 1b**. The wire can serve as a pathway for electrons to flow from the zinc strip to the copper strip.

The second problem is that when the metal strips are placed in their solutions, oxidation begins at the zinc strip and reduction begins at the copper strip—but these reactions cannot continue. The reason is that as zinc is oxidized, positive zinc ions build up around the zinc electrode. As copper in the copper(II) sulfate solution is reduced, negative sulfate ions build up around the copper electrode. The buildup of charges stops any further reaction. To solve this problem, a salt bridge must be added to the system. A **salt bridge** is a pathway to maintain solution neutrality by allowing the passage of ions from one side to another, as shown in **Figure 2**. A salt bridge consists of a tube containing a conducting solution of a soluble salt, such as KCl, held in place by an agar gel or other permeable plug. Ions can move through it, but the solutions cannot.

When the connecting metal wire and the salt bridge are in place, the spontaneous redox reaction begins. Electrons flow through the wire from the oxidation half-reaction to the reduction half-reaction, while positive and negative ions move through the salt bridge. A flow of charged particles is called an electric current. In **Figure 2**, the flow of electrons through the wire and the flow of ions through the salt bridge make up the electric current. The energy of the flowing electrons can be used to light a bulb, as shown in **Figure 2**.

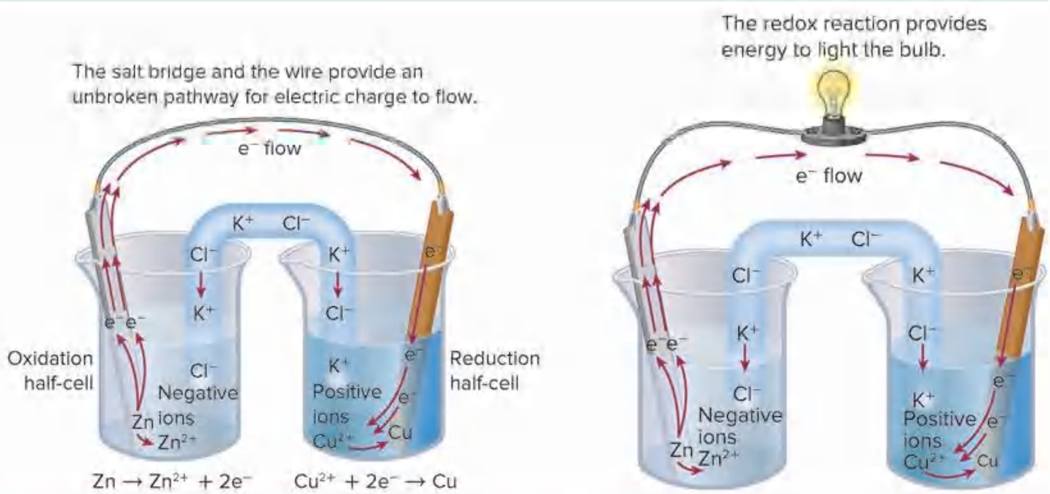


Figure 2 The addition of a salt bridge completes the pathway. Negative ions move through the salt bridge to the zinc side. Positive ions move through the bridge to the copper side.

Figure 3 This replica of one of Alessandro Volta's first cells consists of discs of zinc and copper arranged in alternating layers and separated by cloth or cardboard soaked in an acidic solution. Electric current increased with the number of metal discs used.

Electrochemical cells

The device shown in **Figure 2** is a type of electrochemical cell called a voltaic cell. An **electrochemical cell** is an apparatus that uses a redox reaction to produce electrical energy or uses electrical energy to cause a chemical reaction. A **voltaic cell** is a type of electrochemical cell that converts chemical energy to electrical energy by a spontaneous redox reaction. The voltaic cell is named for Alessandro Volta (1745–1827), the Italian physicist who is credited with its invention in 1800. A replica of one of the first cells he made is shown in **Figure 3.**

Chemistry of Voltaic Cells

An electrochemical cell consists of two parts called **half-cells,** in which the separate oxidation and reduction reactions take place. Each half-cell contains an electrode and a solution containing ions. An electrode is an electrically conductive material, usually a metallic strip or graphite, that conducts electrons into and out of the solution in the half cell. In **Figure 2**, the beaker with the zinc electrode is where the oxidation half of the redox reaction takes place. The beaker with the copper electrode is where the reduction half of the reaction takes place. The reaction that takes place in each half cell is called a half-cell reaction. The electrode where oxidation takes place is called the anode. The electrode where reduction takes place is called the cathode.

Voltaic cells and energy

Recall that an object's potential energy is due to its position or composition. In electrochemistry, electric potential energy is a measure of the amount of current that can be generated from a voltaic cell to do work. Electric charge can flow between two points only when a difference in electric potential energy exists between the two points. In an electrochemical cell, these two points are the two electrodes. Electrons generated at the anode, the site of oxidation, are thought to be pushed or driven toward the cathode by the electromotive force (EMF). This force is due to the difference in electric potential energy between the two electrodes. It is referred to as the cell potential. A volt is a unit used to measure cell potential. The electric potential difference of a voltaic cell is an indication of the energy available to move electrons from the **anode** to the **cathode.**

Figure 4 The roller coaster at the top of the track has high potential energy relative to the track below because of the difference in height. Similarly, an electrochemical cell has potential energy to produce a current because there is a difference in the ability of the electrodes to move electrons from the anode to the cathode.

Consider the analogy illustrated in **Figure 4**. The roller coaster is almost stationary at the top of the track. Then, it plummets from its high position because of the difference in gravitational potential energy (PE) between the top and bottom of the track. The kinetic energy (KE) attained by the roller coaster is determined by the difference in height (potential energy) between the top and bottom parts of the track. Similarly, the energy of the electrons flowing from the anode to the cathode in a voltaic cell is determined by the difference in electric potential energy between the two electrodes. In redox terms, the voltage of a cell is determined by comparing the difference in the tendency of the two electrode materials to accept electrons. The greater the difference, the greater the potential energy difference between the two electrodes and the larger the voltage of the cell will be.

The force of gravity always causes a diver to fall downward to a lower energy state, never upward to a higher energy state. When a diver steps off a diving board, his or her spontaneous motion is always downward. Similarly, in the zinc-copper cell, under standard conditions, copper(II) ions at the cathode accept electrons more readily than the zinc ions at the anode. Thus, the redox reaction occurs spontaneously only when the electrons flow from the zinc to the copper.

Calculating Electrochemical Cell Potentials

Recall that gaining electrons is called reduction. Building on this fact, the tendency of a substance to gain electrons is its **reduction potential.** The reduction potential of an electrode cannot be determined directly because the reduction half-reaction must be coupled with an oxidation half-reaction. When two half-reactions are coupled, the voltage generated corresponds to the difference in potential between the half-reactions. The electrical potential difference between two points is expressed in volts (V).

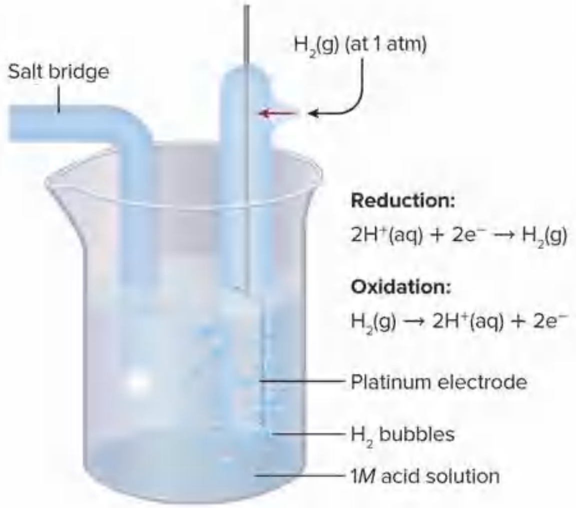


Figure 5 A standard hydrogen electrode consists of a platinum electrode with hydrogen gas at 1 atm pressure bubbling into an acidic solution that is 1*M* in hydrogen ions. The reduction potential for this configuration is defined as 0.000 V.

The standard hydrogen electrode

Long ago, chemists decided to measure the reduction potential of all electrodes against one electrode, the standard hydrogen electrode. The **standard hydrogen electrode** consists of a small sheet of platinum immersed in a hydrochloric acid (HCl) solution that has a hydrogen-ion concentration of 1*M*. Hydrogen gas (H_2), at a pressure of 1 atm is bubbled in, and the temperature is maintained at 25°C, as shown in **Figure 5**. The potential, also called the standard reduction potential (E^0), of this standard hydrogen electrode is defined as 0.000 V. This electrode can act as an oxidation half-reaction or a reduction half-reaction, depending on the half-cell to which it is connected. The two possible reactions that can take place at the hydrogen electrode are shown in the following chemical equation.

$$2H^+(aq) + 2e^- \underset{\text{Oxidation}}{\overset{\text{Reduction}}{\rightleftharpoons}} H_2(g) \qquad E^0 = 0.000\text{ V}$$

Half-cell potentials

Over the years, chemists have measured and recorded the standard reduction potentials of many different half-cells. **Table 1** lists some common half-cell reactions in order of increasing reduction potential. The values in the table were obtained by measuring the potential when each half-cell was connected to a standard hydrogen half-cell.

ACADEMIC VOCABULARY

correspond

to be in agreement or to match

Her directions correspond with the map.

CCC CROSSCUTTING CONCEPTS

Patterns Write a paragraph describing the patterns that you observe in voltaic cells.

All of the half-reactions in **Table 1** are written as reductions. However, in any voltaic cell, which always contains two spontaneous half-reactions, the half-reaction with the lower reduction potential will proceed in the opposite direction and will be an oxidation reaction. In other words, the half-reaction that is more positive will proceed as a reduction, and the half-reaction that is more negative will proceed as an oxidation.

The electrode being measured must also be under standard conditions, that is, immersed in a 1*M* solution of its ions at 25°C and 1 atm. The superscript zero in the notation E^0 is a shorthand way of indicating "measured under standard conditions."

Table 1 **Standard Reduction Potentials**

Half-Reaction	E^0(V)	Half-Reaction	E^0(V)
$Li^+ + e^- \rightleftharpoons Li$	−3.0401	$Cu^{2+} + e^- \rightleftharpoons Cu^+$	+0.153
$Ca^{2+} + 2e^- \rightleftharpoons Ca$	−2.868	$Cu^{2+} + 2e^- \rightleftharpoons Cu$	+0.3419
$Na^+ + e^- \rightleftharpoons Na$	−2.71	$O_2 + 2H_2O + 4e^- \rightleftharpoons 4OH^-$	+0.401
$Mg^{2+} + 2e^- \rightleftharpoons Mg$	−2.372	$I_2 + 2e^- \rightleftharpoons 2I^-$	+0.5355
$Be^{2+} + 2e^- \rightleftharpoons Be$	−1.847	$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	+0.771
$Al^{3+} + 3e^- \rightleftharpoons Al$	−1.662	$NO_3^- + 2H^+ + e^- \rightleftharpoons NO_2 + H_2O$	+0.775
$Mn^{2+} + 2e^- \rightleftharpoons Mn$	−1.185	$Hg_2^{2+} + 2e^- \rightleftharpoons 2Hg$	+0.7973
$Cr^{2+} + 2e^- \rightleftharpoons Cr$	−0.913	$Ag^+ + e^- \rightleftharpoons Ag$	+0.7996
$2H_2O + 2e^- \rightleftharpoons H_2 + 2OH^-$	−0.8277	$Hg^{2+} + 2e^- \rightleftharpoons Hg$	+0.851
$Zn^{2+} + 2e^- \rightleftharpoons Zn$	−0.7618	$2Hg^{2+} + 2e^- \rightleftharpoons Hg_2^{2+}$	+0.920
$Cr^{3+} + 3e^- \rightleftharpoons Cr$	−0.744	$NO_3^- + 4H^+ + 3e^- \rightleftharpoons NO + 2H_2O$	+0.957
$S + 2e^- \rightleftharpoons S^{2-}$	−0.47627	$Br_2(l) + 2e^- \rightleftharpoons 2Br^-$	+1.066
$Fe^{2+} + 2e^- \rightleftharpoons Fe$	−0.447	$Pt^{2+} + 2e^- \rightleftharpoons Pt$	+1.18
$Cd^{2+} + 2e^- \rightleftharpoons Cd$	−0.4030	$O_2 + 4H^+ + 4e^- \rightleftharpoons 2H_2O$	+1.229
$PbI_2 + 2e^- \rightleftharpoons Pb + 2I^-$	−0.365	$Cl_2 + 2e^- \rightleftharpoons 2Cl^-$	+1.35827
$PbSO_4 + 2e^- \rightleftharpoons Pb + SO_4^{2-}$	−0.3588	$Au^{3+} + 3e^- \rightleftharpoons Au$	+1.498
$Co^{2+} + 2e^- \rightleftharpoons Co$	−0.28	$MnO_4^- + 8H^+ + 5e^- \rightleftharpoons Mn^{2+} + 4H_2O$	+1.507
$Ni^{2+} + 2e^- \rightleftharpoons Ni$	−0.257	$Au^+ + e^- \rightleftharpoons Au$	+1.692
$Sn^{2+} + 2e^- \rightleftharpoons Sn$	−0.1375	$H_2O_2 + 2H^+ + 2e^- \rightleftharpoons 2H_2O$	+1.776
$Pb^{2+} + 2e^- \rightleftharpoons Pb$	−0.1262	$Co^{3+} + e^- \rightleftharpoons Co^{2+}$	+1.92
$Fe^{3+} + 3e^- \rightleftharpoons Fe$	−0.037	$S_2O_8^{2-} + 2e^- \rightleftharpoons 2SO_4^{2-}$	+2.010
$2H^+ + 2e^- \rightleftharpoons H_2$	**0.0000**	$F_2 + 2e^- \rightleftharpoons 2F^-$	+2.866

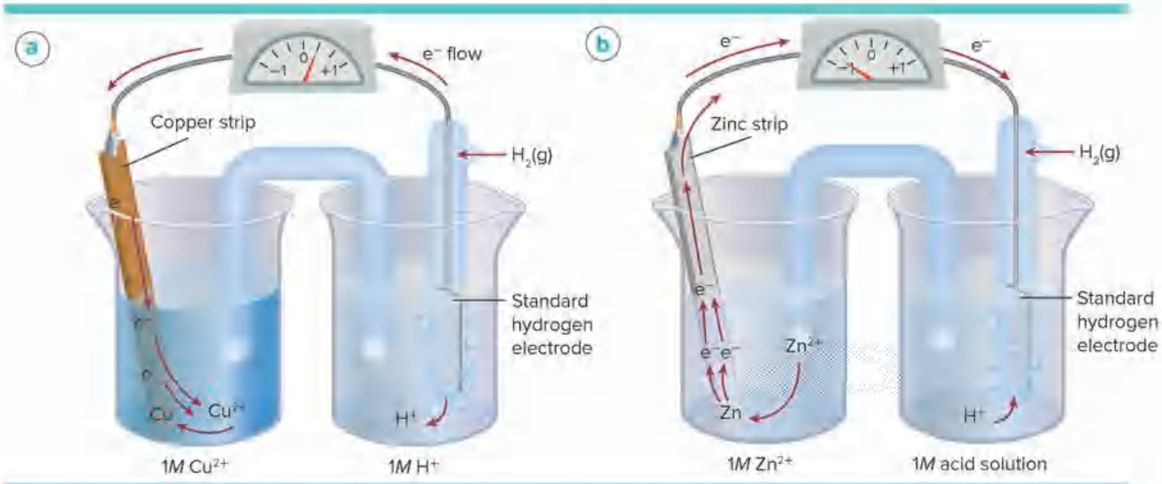


Figure 6 **a.** When a Cu^{2+} | Cu electrode is connected to the hydrogen electrode, electrons flow toward the copper strip and reduce Cu^{2+} ions to Cu atoms. **b.** When a Zn | Zn^{2+} electrode is connected to the hydrogen electrode, electrons flow away from the zinc strip and zinc atoms are oxidized to Zn^{2+} ions.

Determining electrochemical cell potentials

You can use **Table 1** to calculate the electric potential of a voltaic cell consisting of a copper electrode and a zinc electrode under standard conditions. The first step is to determine the standard reduction potential for the copper half-cell (E^0_{Cu}). When the copper electrode is attached to a standard hydrogen electrode, as in **Figure 6a**, electrons flow from the hydrogen electrode to the copper electrode, and copper ions are reduced to copper metal. The E^0, measured by a voltmeter, is +0.342 V. The positive voltage indicates that Cu^{2+} ions at the copper electrode accept electrons more readily than do H^+ ions at the standard hydrogen electrode. Therefore, oxidation takes place at the hydrogen electrode, and reduction takes place at the copper electrode.

$$H_2(g) \rightarrow 2H^+(aq) + 2e^- \text{ (oxidation half-cell reaction)}$$
$$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s) \text{ (reduction half-cell reaction)}$$
$$H_2(g) + Cu^{2+}(aq) \rightarrow 2H^+(aq) + Cu(s) \text{ (overall redox reaction)}$$

This reaction can be written in a form called cell notation.

Reactant Product Reactant Product

$$H_2 \mid H^+ \parallel Cu^{2+} \mid Cu \qquad E^0_{Cu} = +0.342\text{ V}$$

Oxidation half-cell Reduction half-cell

The two participants in the oxidation reaction are written first in reactant | product order. They are followed by a double vertical line (||) representing the connection between the half-cells. Then, the two participants in the reduction reaction are written in reactant | product order. For positive values of E^0, it is customary to place a plus sign before the voltage. Also looks like there is a little padding at the bottom of the page that can be used to increase the size of figure 6

The next step is to determine the standard reduction potential for the zinc half-cell (E^0_{Zn}). When the zinc electrode is measured against the standard hydrogen electrode under standard conditions, as in **Figure 6b**, electrons flow from the zinc electrode to the hydrogen electrode. The E^0 of the zinc half-cell, measured by a voltmeter, is –0.762 V. This means that the H^+ ions at the hydrogen electrode accept electrons more readily than do the zinc ions. Thus, the hydrogen ions have a higher reduction potential than the zinc ions. Recall that the hydrogen electrode is assigned a zero potential, so the reduction potential of the zinc electrode must have a negative value. The two half-cell reactions and the overall reaction are written as follows.

$$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^- \text{ (oxidation half-cell reaction)}$$

$$2H^+(aq) + 2e^- \rightarrow H_2(g) \text{ (reduction half-cell reaction)}$$

$$Zn(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2(g) \text{ (overall redox reaction)}$$

This reaction can be written in the following cell notation.

Reactant Product Reactant Product

$$Zn \mid Zn^{2+} \parallel H^+ \mid H_2 \qquad E^0_{Zn} = -0.762 \text{ V}$$

Oxidation half-cell   Reduction half-cell

The final step in calculating electrochemical cell potential is to combine the copper and zinc half-cells as a voltaic cell. This means calculating the voltaic cell's standard potential using the following formula.

Formula for Cell Potential

$$E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$$

E^0_{cell} represents the overall standard cell potential.

$E^0_{reduction}$ represents the standard half-cell potential for the reduction.

$E^0_{oxidation}$ represents the standard half-cell potential for the oxidation.

The standard potential of a cell is the standard potential of the reduction half-cell minus the standard potential of the oxidation half-cell.

Because reduction occurs at the copper electrode and oxidation occurs at the zinc electrode, the E^0 values are substituted as follows.

$$\begin{aligned} E^0_{cell} &= E^0_{Cu^{2+}|Cu} - E^0_{Zn^{2+}|Zn} \\ &= +0.342 \text{ V} - (-0.762 \text{ V}) \\ &= +1.104 \text{ V} \end{aligned}$$

Notice that the negative sign in the formula automatically changes the sign of the oxidation half-reaction, so you do not reverse the sign of the standard reduction potentials listed in **Table 1** when they are used for the oxidation half-reaction.

EXAMPLE Problem 1

CALCULATE A CELL POTENTIAL The following reduction half-reactions represent the half-cells of a voltaic cell.

$$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$$

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

Determine the overall cell reaction and the standard cell potential. Describe the cell using cell notation.

1 ANALYZE THE PROBLEM

You are given the half-cell equations and can find standard reduction potentials in **Table 1.** The half-reaction with the lower reduction potential will be an oxidation. With this information, you can write the overall cell reaction, calculate the standard cell potential, and describe the cell in cell notation.

Known
Standard reduction potentials for the half-cells
$E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$

Unknown
overall cell reaction = ?
E^0_{cell} = ?
cell notation = ?

2 SOLVE FOR THE UNKNOWN

Find the standard reduction potentials of each half-reaction in **Table 1.**

$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$ $\quad E^0_{I_2|I^-} = +0.536\ V$

$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$ $\quad E^0_{Fe^{2+}|Fe} = -0.447\ V$

The reduction of iodine has the higher reduction potential, so this half-reaction proceeds in the forward direction as a reduction. The iron half-reaction proceeds in the reverse direction as an oxidation.

$I_2(s) + 2e^- \rightarrow 2I^-(aq)$ (reduction half-cell reaction)

$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$ (oxidation half-cell reaction) — Rewrite the iron half-reaction in the correct direction.

$I_2(s) + Fe(s) \rightarrow Fe^{2+}(aq) + 2I^-(aq)$ — Add the two equations.

The overall cell reaction is $I_2(s) + Fe(s) \rightarrow Fe^{2+}(aq) + 2I^-(aq)$.

Calculate the standard cell potential.

$E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$ — State the formula for cell potential.

$E^0_{cell} = E^0_{I_2|I^-} - E^0_{Fe^{2+}|Fe}$ — Substitute $E^0_{I_2|I^-}$ and $E^0_{Fe^{2+}|Fe}$ in the generic equation.

$E^0_{cell} = +0.536\ V - (-0.447\ V)$ — Substitute $E^0_{I_2|I^-} = +0.536\ V$ and $E^0_{Fe^{2+}|Fe} = -0.447\ V$.

$E^0_{cell} = +0.983\ V$

Describe the cell using cell notation.

$Fe\ |\ Fe^{2+}$ — First, write the oxidation half-reaction using cell notation: reactant then product.

$Fe\ |\ Fe^{2+}\ ||\ I_2|I^-$ — Next, write the reduction half-reaction to the right. Separate the half-cells by a double vertical line.

Cell notation: $Fe\ |\ Fe^{2+}\ ||\ I_2\ |\ I^-$

3 EVALUATE THE ANSWER

The calculated potential is reasonable given the potentials of the half-cells. E^0 is reported to the correct number of significant figures.

PRACTICE Problems ADDITIONAL PRACTICE

For each of these pairs of half-reactions, write the balanced equation for the overall cell reaction, and calculate the standard cell potential. Describe the reaction using cell notation. Refer to the module on redox reactions to review writing and balancing redox equations.

1. $Pt^{2+}(aq) + 2e^- \rightleftharpoons Pt(s)$ and $Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$

2. $Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$ and $Cr^{3+}(aq) + 3e^- \rightleftharpoons Cr(s)$

3. $Hg^{2+}(aq) + 2e^- \rightleftharpoons Hg(l)$ and $Cr^{2+}(aq) + 2e^- \rightleftharpoons Cr(s)$

4. CHALLENGE Write the balanced equation for the cell reaction and calculate the standard cell potential for the reaction that occurs when these half-cells are connected. Describe the reaction using cell notation.

$NO_3^- + 4H^+ + 3e^- \rightleftharpoons NO + 2H_2O$

$O_2 + 2H_2O + 4e^- \rightleftharpoons 4OH^-$

Using Standard Reduction Potentials

The Example Problem showed you how to use the data from **Table 1** to calculate the standard potential (voltage) of voltaic cells. Another important use of standard reduction potentials is to determine if a proposed reaction under standard conditions will be spontaneous. How can standard reduction potentials indicate spontaneity? Electrons in a voltaic cell always flow from the half-cell with the lower standard reduction potential to the half-cell with the higher standard reduction potential, giving a positive cell voltage. To predict whether any proposed redox reaction will occur spontaneously, simply write the process in the form of half-reactions and look up the reduction potential of each. Use the values to calculate the potential of a voltaic cell operating with these two half-cell reactions. If the calculated potential is positive, the reaction is spontaneous. If the value is negative, the reaction is not spontaneous. However, the reverse of a nonspontaneous reaction will occur because it will have a positive cell voltage, which means that the reverse reaction is spontaneous.

Get It?

Identify the sign of the potential of a redox reaction that occurs spontaneously.

PRACTICE Problems ADDITIONAL PRACTICE

Calculate the cell potential to determine if each of the following balanced redox reactions is spontaneous as written. Use Table 1 to help you determine the correct half-reactions.

5. $Sn(s) + Cu^{2+}(aq) \rightarrow Sn^{2+}(aq) + Cu(s)$

6. $Mg(s) + Pb^{2+}(aq) \rightarrow Pb(s) + Mg^{2+}(aq)$

7. $2Mn^{2+}(aq) + 8H_2O(l) + 10Hg^{2+}(aq) \rightarrow$
$2MnO_4^-(aq) + 16H^+(aq) + 5Hg_2^{2+}(aq)$

8. $2SO_4^{2-}(aq) + Co^{2+}(aq) \rightarrow Co(s) + S_2O_8^{2-}(aq)$

9. CHALLENGE Using **Table 1**, write the equation and determine the cell voltage (E^0) for the following cell. Is the reaction spontaneous?

$Al \mid Al^{3+} \parallel Hg^{2+} \mid Hg_2^{2+}$

In summary, when given two half-reactions for a cell, follow these steps to write the overall equation and determine the cell potential.

1. Find the two half-reactions and their standard reduction potentials in **Table 1.**
2. Compare the two half-cell potentials. The one with the higher reduction potential is the half-cell in which reduction will occur. Oxidation will occur in the half-cell with the lower reduction potential.
3. Write the equation for the reduction as it is shown in **Table 1.** Write the oxidation equation in the opposite direction.
4. Balance the electrons in the two half-cell equations by multiplying each by a factor. Add the equations.
5. Use the formula $E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$ to obtain the cell potential.

Check Your Progress

Summary

- In a voltaic cell, oxidation and reduction take place at electrodes separated from each other.
- The standard potential of a half-cell reaction is its voltage when paired with a standard hydrogen electrode under standard conditions.
- The reduction potential of a half-cell is negative if it undergoes oxidation when connected to a standard hydrogen electrode. The reduction potential of a half-cell is positive if it undergoes reduction when connected to a standard hydrogen electrode.
- The standard potential of a voltaic cell is the difference between the standard reduction potentials of the half-cell reactions.

Demonstrate Understanding

10. **Describe** the conditions under which a redox reaction causes an electric current to flow through a wire.
11. **Identify** the components of a voltaic cell. Explain the role of each component in the operation of the cell.
12. **Write** the balanced equation for the spontaneous cell reaction that occurs in a cell with these reduction half-reactions.
    a. $Ag^+(aq) + e^- \rightleftharpoons Ag(s)$ and $Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$
    b. $Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$ and $2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$
    c. $Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$ and $Fe^{3+}(aq) + 3e^- \rightleftharpoons Fe(s)$
    d. $PbI_2(s) + 2e^- \rightleftharpoons Pb(s) + 2I^-(aq)$ and $Pt^{2+}(aq) + 2e^- \rightleftharpoons Pt(s)$
13. **Determine** the standard potential for electrochemical cells in which each equation represents the overall cell reaction. Identify the reactions as spontaneous or nonspontaneous as written.
    a. $2Al^{3+}(aq) + 3Cu(s) \rightarrow 3Cu^{2+}(aq) + 2Al(s)$
    b. $Hg^{2+}(aq) + 2Cu^+(aq) \rightarrow 2Cu^{2+}(aq) + Hg(l)$
    c. $Cd(s) + 2NO_3^-(aq) + 4H^+(aq) \rightarrow Cd^{2+}(aq) + 2NO_2(g) + 2H_2O(l)$
14. **Design** a concept map for Lesson 1, starting with the term *electrochemical cell.* Incorporate all the new vocabulary terms in your map.

LEARNSMART® Go online to follow your personalized learning path to review, practice, and reinforce your understanding.

LESSON 2
BATTERIES

FOCUS QUESTION

How do voltaic cells improve or cause problems in our daily lives?

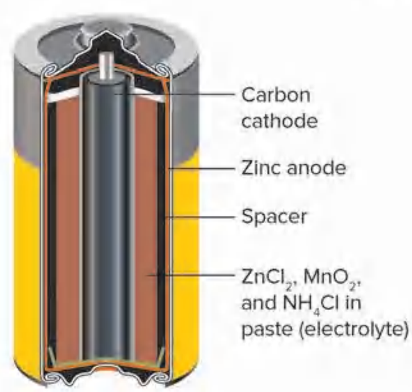
Dry Cells

Some of the spontaneous cell reactions you have been reading about provide the energy of the batteries that you use every day. A **battery** is one or more voltaic cells in a single package that generates electric current. From the time of its invention in the 1860s until recently, the most commonly used voltaic cell was the zinc-carbon dry cell, shown in **Figure 7**.

Zinc-carbon dry cells

A **dry cell** is an electrochemical cell in which the electrolyte is a moist paste. The paste in a zinc-carbon dry cell consists of zinc chloride, manganese(IV) oxide, ammonium chloride, and a small amount of water inside a zinc case. The zinc shell is the cell's anode, where the oxidation of zinc metal occurs according to the following equation.

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



Zinc-carbon dry cell

Figure 7 Dry cells contain a moist paste in which the cathode half-reaction takes place. In the zinc-carbon dry cell, the zinc case acts as the anode.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practices: Batteries—Reduce, Reuse, Recycle, Recover

HS-ESS3-4. Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the module question?

A carbon (graphite) rod in the center of the dry cell serves as the cathode, but the reduction half-cell reaction takes place in the paste. The carbon rod in this type of dry cell is called an inactive cathode because it idoes not participate in the redox reaction. Its purpose is to conduct electrons. The reduction half-cell reaction is as follows.

$$2NH_4^+(aq) + 2MnO_2(s) + 2e^- \rightarrow Mn_2O_3(s) + 2NH_3(aq) + H_2O(l)$$

In the zinc-carbon dry cell, a spacer made of a porous material and damp from the liquid in the paste separates the paste from the zinc anode. The spacer acts as a salt bridge. The zinc-carbon dry cell produces a voltage of 1.5 V until ammonia comes out of solution as a gas. At that point, the voltage is so low that the battery becomes useless.

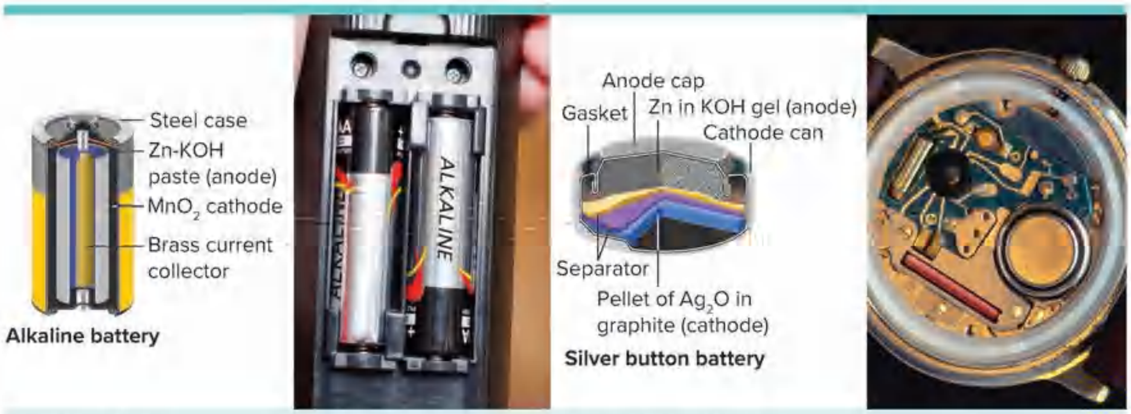
Alkaline batteries

More-efficient dry cells are shown in **Figure 8**. In the alkaline cell, the zinc is in a powdered form, which provides more surface area for reaction. The zinc is mixed in a paste with potassium hydroxide, a strong base, and the paste is contained in a steel case. The cathode mixture is manganese(IV) oxide, also mixed with potassium hydroxide. Alkaline batteries do not need the carbon rod cathode, so they can be made smaller than zinc-carbon dry cells. The anode half-cell reaction is as follows.

$$Zn(s) + 2OH^-(aq) \rightarrow ZnO(s) + H_2O(l) + 2e^-$$

The cathode half-cell reaction is as follows.

$$MnO_2(s) + 2H_2O(s) + 2e^- \rightarrow Mn(OH)_2(s) + 2OH^-(aq)$$



Alkaline battery

The alkaline battery uses powdered zinc in an alkaline paste as the anode.

Silver button battery

Although it looks different, the silver battery is much like the alkaline battery. The silver battery uses silver oxide (Ag_2O) in the cathode instead of manganese(IV) oxide (MnO_2).

Figure 8 Alkaline batteries are more efficient than zinc-carbon dry cells and are useful when smaller batteries are needed. Silver button batteries are even smaller, making them well suited to devices such as watches.

Silver batteries

The silver battery shown in **Figure 8** is even smaller and is used to power devices such as hearing aids, watches, and cameras. The silver battery uses the same anode half-reaction as the alkaline battery, with the following cathode half-reaction.

$$Ag_2O(s) + H_2O(l) + 2e^- \rightarrow 2Ag(s) + 2OH^-(aq)$$

Get It?

Identify the half-reaction that is similar in both alkaline and silver batteries.

Primary and secondary batteries

Batteries are divided into two types, depending on their chemical processes. The zinc-carbon, alkaline-zinc, and silver cells are classified as primary batteries. **Primary batteries** produce electric energy by means of redox reactions that are not easily reversed. These cells deliver current until the reactants are gone, and then the battery must be discarded. Other batteries, called **secondary batteries,** depend on reversible redox reactions, so they are rechargeable. A car battery and the battery in a laptop computer are examples of secondary batteries, which are sometimes called storage batteries.

Storage batteries that power devices such as cordless drills and screwdrivers are usually nickel-cadmium rechargeable batteries, sometimes called NiCad batteries, as shown in **Figure 9**. For maximum efficiency, the anode and cathode are long, thin ribbons of material separated by a layer through which ions can pass. The ribbons are wound into a coil and packaged in a steel case. The anode reaction that occurs when the battery is used to generate electric current is the oxidation of cadmium in the presence of a base.

$$Cd(s) + 2OH^-(aq) \rightarrow Cd(OH)_2(s) + 2e^-$$

The cathode reaction is the reduction of nickel from the +3 to the +2 oxidation state.

$$NiO(OH)(s) + H_2O(l) + e^- \rightarrow Ni(OH)_2(s) + OH^-(aq)$$

When the battery is recharged, these reactions are reversed. The battery is plugged into an electric outlet, which supplies electrical energy. This energy drives the reverse reactions, which are nonspontaneous. When a battery is recharging, electric energy is being transformed into chemical energy. Once the battery is in use again, it transforms chemical energy into electric energy.

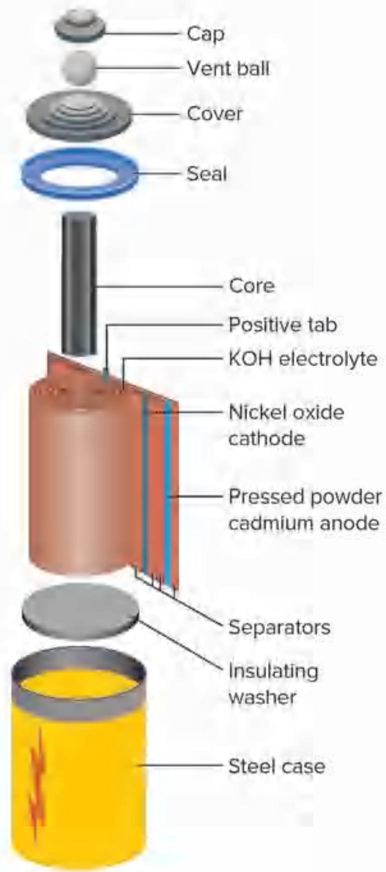


Figure 9 Cordless tools and phones are often powered by rechargeable batteries, such as the NiCad battery. The battery pack is recharged by plugging it into an electric outlet, which supplies the power to drive the nonspontaneous recharge reaction.

Get It?

Compare the energy transformations that take place in batteries when they are in use and when they are being recharged.

Lead-Acid Storage Battery

Another common storage battery is the lead-acid battery used in automobiles. Most auto batteries contain six cells that generate about 2 V each for a total output of 12 V. The anode of each cell consists of two or more grids of porous lead, and the cathode consists of lead grids filled with lead(IV) oxide. This type of battery should probably be called a lead-lead(IV) oxide battery, but the term lead-acid is commonly used because the battery's electrolyte is a solution of sulfuric acid.

The lead-acid battery is not a dry cell. The following equation represents the oxidation half-cell reaction at the anode where lead is oxidized from the zero oxidation state to the +2 oxidation state in $PbSO_4$.

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

The reduction of lead from the +4 to the +2 oxidation state takes place at the cathode. The half-cell reaction for the cathode is

$$PbO_2(s) + 4H^+(aq) + SO_4^{2-}(aq) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(l).$$

The overall reaction is

$$Pb(s) + PbO_2(s) + 4H^+(aq) + 2SO_4^{2-}(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l).$$

By looking at the half-cell reactions, you can see that lead(II) sulfate ($PbSO_4$) is the reaction product in both oxidation and reduction. Also, Pb, PbO_2, and $PbSO_4$ are solid substances, so they stay in place where they are formed. Thus, whether the battery is discharging or charging, the reactants are available where they are needed.

Sulfuric acid serves as the electrolyte in the battery, but, as the overall cell equation shows, it is depleted as the battery generates electric current. What happens when the battery is recharging? In this case, the reactions reverse, forming lead and lead(IV) oxide and releasing sulfuric acid, shown as $4H^+(aq) + 2SO_4^{2-}(aq)$ in the equation.

The lead-storage battery shown in **Figure 10** is a good choice for motor vehicles because it provides a large initial supply of energy to start the engine, has a long shelf life, and is reliable at low temperatures.

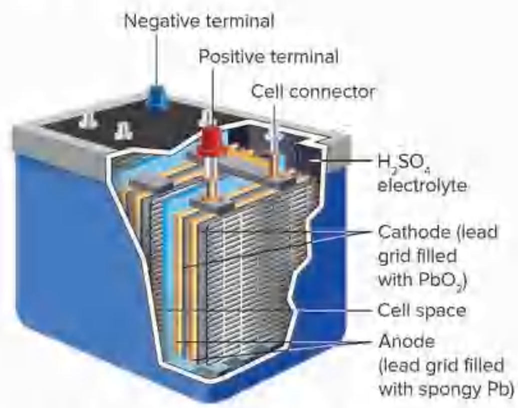


Figure 10 Lead-acid batteries contain lead plates and lead(IV) oxide plates. The electrolyte is a solution of sulfuric acid. When the battery is in use, the sulfuric acid is depleted and the electrolyte becomes less dense. The lead-acid battery used in automobiles discharges when it starts the car and charges when the engine is running.

Get It?

Compare and contrast dry cells and lead-acid storage batteries.

Lithium Batteries

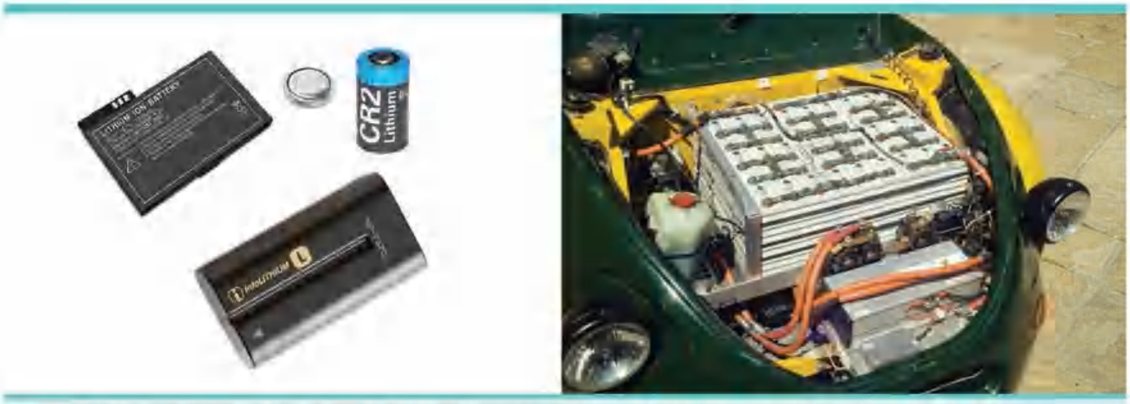
Although lead-acid batteries are reliable and suitable for many applications, engineers have been working to develop batteries with less mass and higher capacity to power devices from wristwatches to electric cars. For applications in which a battery is the key component and must provide a significant amount of power, such as for the operation of an electric car, lead-acid batteries are too heavy to be feasible.

The solution is to develop lightweight batteries that store a large amount of energy for their size. Engineers have focused their attention on the element lithium for two reasons: lithium is the lightest known metal and has the lowest standard reduction potential of the metallic elements, -3.04 V, as shown in **Table 1**. A battery that oxidizes lithium at the anode can generate almost 2.3 V more than a similar battery in which zinc is oxidized.

Compare the zinc and lithium oxidation half-reactions and their standard reduction potentials.

$$Zn \rightarrow Zn^{2+} + 2e^- \qquad (E^0_{Zn^{2+}|Zn} = -0.762\ V)$$
$$Li \rightarrow Li^+ + e^- \qquad (E^0_{Li^+|Li} = -3.04\ V)$$
$$E^0_{Zn^{2+}|Zn} - E^0_{Li^+|Li} = +2.28\ V$$

Figure 11 shows a range of available lithium batteries and a developing application.



Lithium batteries often deliver either 3 V or 9 V and come in many sizes to fit different devices.

Lithium battery packs power this experimental car to a maximum speed of 113 km/h. The car has a range of over 320 km.

Figure 11 The light weight, long life, and high potential of a lithium battery make it an excellent choice for a variety of purposes.

WORD ORIGIN

capacity

capac-, capax, from Latin, meaning *containing or capable of holding a great deal*

Lithium batteries can be either primary or secondary batteries, depending on which reduction reactions are coupled to the oxidation of lithium. For example, some lithium batteries use the same cathode reaction as zinc-carbon dry cells, the reduction of manganese(IV) oxide (MnO_2) to manganese(III) oxide (Mn_2O_3). These batteries produce an electric potential of about 3 V compared to 1.5 V for zinc-carbon cells. Lithium batteries last much longer than other kinds of batteries. As a result, they are often used in watches, computers, and cameras to maintain time, date, memory, and personal settings—even when the device is turned off.

Get It?
List three advantages of lithium batteries.

Fuel Cells

When hydrogen burns in air, it does so explosively, with the evolution of light and heat.

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) + \text{energy}$$

Can this reaction occur under controlled conditions inside a cell? Yes, it can.

PHYSICS Connection A **fuel cell** is a voltaic cell in which the oxidation of a fuel is used to produce electric energy. Fuel cells differ from other batteries because they are provided with a continual supply of fuel from an external source.

Many people think the fuel cell is a modern invention, but the first one was demonstrated in 1839 by William Grove (1811–1896), a British electrochemist. He called his cell a "gas battery." Grove did not pursue the development of his invention, but other scientists worked on the concept and in 1932, Dr. Francis Thomas Bacon (1904–1992) succeeded in making a fuel cell that was able to power a welding machine. Still, it was not until the 1950s, when scientists began working in earnest on the space program, that efficient, practical fuel cells were developed. If astronauts were to fly a space shuttle, supplies of water were needed to support their lives on board and a reliable source of electricity was needed to power the shuttle's many systems. Both of these primary needs were met with the development of the hydrogen fuel cell that controls the oxidation of hydrogen and provides both electricity and water. The cell produces no by-products to require disposal or storage on a space journey.

Real-World Chemistry
Fuel Cells

REDUCING POLLUTION One of the largest sources of air pollution in many cities is vehicles. In some European cities, experimental buses powered by hydrogen fuel cells are making a difference. Exhaust from these buses contain no carbon dioxide and no oxides of nitrogen or sulfur. Pure water is their only product.

Fuel cells are more efficient than engines that burn fossil fuel. They are also considered much cleaner because their only product is pure water. Why are they not in everyday use? There are several barriers to the widespread use of fuel cells. These barriers include the financial and environmental costs of producing pure hydrogen and of setting up infrastructure for fueling vehicles that use hydrogen fuel cells for power.

How a fuel cell works

As in other voltaic cells, a fuel cell has an anode and a cathode and requires an electrolyte so that ions can migrate between electrodes. A common electrolyte in a fuel cell is an alkaline solution of potassium hydroxide. Each electrode is a hollow chamber of porous carbon walls that allows contact between the inner chamber and the electrolyte surrounding it. The following oxidation half-reaction takes place at the anode.

$$2H_2(g) + 4OH^-(aq) \rightarrow 4H_2O(l) + 4e^-$$

The reaction uses the hydroxide ions that are abundant in the alkaline electrolyte and releases electrons to the anode. Electrons released by the oxidation of hydrogen flow through the external circuit to the cathode where the following reduction half-reaction takes place.

$$O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$$

The electrons reduce oxygen in the presence of water to form four hydroxide ions, which replenish the hydroxide ions that are used up at the anode. When the two half-reactions are combined, the equation is the same as the equation for the burning of hydrogen in oxygen.

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$$

Advantages of fuel cells

Because the fuel for the cell is provided from an outside source, fuel cells never run down as batteries do. They keep producing electricity as long as fuel is available. Fuel cells are very reliable and can also be compact and lightweight. They are most useful today as power sources in remote places, such as in space, submarines, and rural or wilderness weather stations.

Some fuel cells use fuels other than hydrogen. For example, methanol replaces hydrogen in some cells, but has the disadvantage of producing carbon dioxide as an exhaust gas.

Get It?

Compare fuel cells with other voltaic cells to find an important way in which they are different.

STEM CAREER Connection

Fuel Cell Engineer

Are you concerned about air pollution caused by our transportation systems? Do you want to develop technologies that will help the world meet its energy needs in the future? Fuel cell engineers design, test and build fuel-cell systems and parts.

Figure 12 A "stack" of PEM-type cells can generate enough energy to power an electric car.

When used in practical devices, fuel cells actually consist of many layers of individual cells. Together, these layers are called a fuel cell stack. Fuel cells such as the one shown in **Figure 12** use a plastic sheet called a proton-exchange membrane (PEM), which eliminates the need for a liquid electrolyte.

Corrosion

In this chapter, you have examined the spontaneous redox reactions in voltaic cells. Spontaneous redox reactions also occur in nature. An example is the corrosion of iron, usually called rusting. **Corrosion** is the loss of metal resulting from an oxidation-reduction reaction of the metal with substances in the environment. Although rusting is usually thought of as a reaction between iron and oxygen, it is more complex. Both water and oxygen must be present for rusting to occur. For this reason, an iron object, such as the one shown in **Figure 13**, that has been left exposed to air and moisture is especially susceptible to rust. The portion that is in contact with the moist ground rusted first.

Get It?
Name the substances involved in the corrosion of iron.

Figure 13 Left unattended in the presence of air and moisture, this iron barrel is slowly being oxidized to rust (Fe_2O_3).

Rusting usually begins where there is a pit or a small break in the surface of the iron. This region becomes the anode of the cell as iron atoms begin to lose electrons as illustrated in **Figure 14**.

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

The iron(II) ions become part of the water solution, while the electrons move through the iron to the cathode region. In effect, the piece of iron becomes the external circuit as well as the anode. The cathode is usually located at the edge of the water drop where water, iron, and air come in contact. Here, the electrons reduce oxygen from the air in the following half-reaction.

$$O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$$

The supply of H^+ ions is probably furnished by carbonic acid formed when CO_2 from air dissolves in water. Next, the Fe^{2+} ions in solution are oxidized to Fe^{3+} ions by reacting with oxygen dissolved in the water. The Fe^{3+} ions combine with oxygen to form insoluble Fe_2O_3, rust.

$$4Fe^{2+}(aq) + 2O_2(g) + 2H_2O(l) + 4e^- \rightarrow 2Fe_2O_3(s) + 4H^+(aq)$$

Combining the three equations yields the overall cell reaction for the corrosion of iron.

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

Rusting is a slow process because water droplets have few ions and, therefore, are not good electrolytes. However, if the water contains abundant ions, as in seawater or in regions where roads are salted in the winter, corrosion occurs much faster because the solutions are excellent electrolytes.

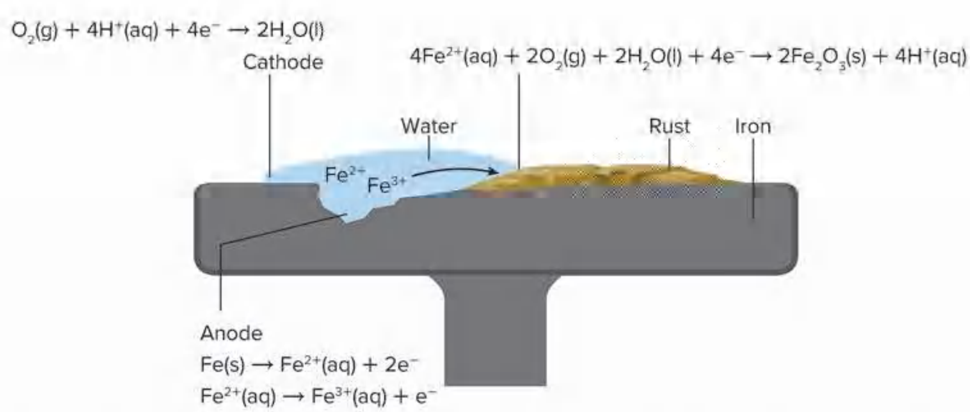


Figure 14 Corrosion occurs when air, water, and iron set up a voltaic cell similar to the conditions shown at the surface of this iron I-beam. An I-beam is a large piece of iron shaped like the capital letter I and used in the construction of large buildings.

Name *the two species that are oxidized at the anode.*

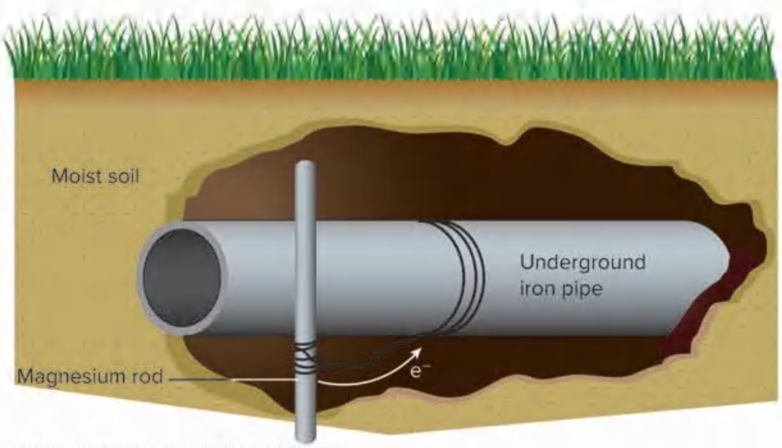
Figure 15 Because corrosion can cause considerable damage, it is important to find ways to prevent rust and deterioration. Paint or another protective coating is one way to protect steel structures from corrosion.

Preventing corrosion

Corrosion of cars, bridges, ships, the structures of buildings, and other metallic objects causes more than $100 billion in damage a year in the United States. For this reason, several means to minimize corrosion have been devised. One example is to apply a coat of paint to seal out both air and moisture, but because paint deteriorates over time, objects such as the bridge shown in **Figure 15** must be repainted often.

The steel hulls of ships are constantly in contact with salt water, so the prevention of corrosion is vital. Although the hull can be painted, another method is used to minimize corrosion. Blocks of metals, such as magnesium, aluminum, or titanium, are placed in contact with the steel hull. These blocks oxidize more easily than iron and become the anode of the corrosion cell. They are called sacrificial anodes because they are corroded, while the iron in the hull is spared. A similar technique is used to protect underground iron pipes. Magnesium bars are attached to the pipe by wires, and these bars corrode instead of the pipe, as shown in **Figure 16**.

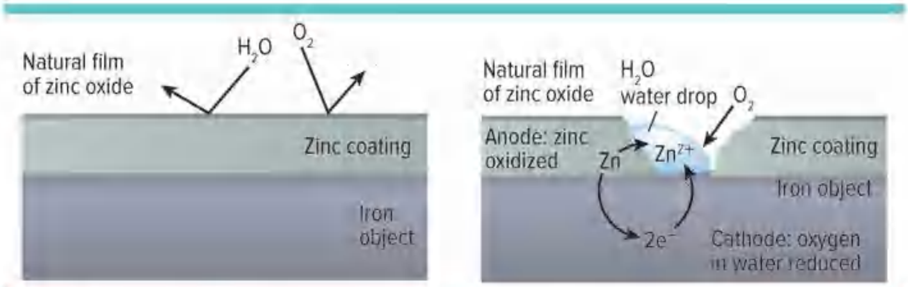
Another approach to preventing corrosion is to coat iron with another metal that is more resistant to corrosion. In the **galvanization** process, iron is coated with a layer of zinc by either dipping the object into molten zinc or by electroplating the zinc onto it. Although zinc is more readily oxidized than iron, it is one of the self-protecting metals, a group that also includes aluminum and chromium. When exposed to air, these metals oxidize at the surface, creating a thin metal-oxide coating that seals the metal from further oxidation.



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

Reduction: $O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$

Figure 16 Sacrificial anodes of magnesium or other active metals are used to prevent corrosion. A magnesium rod attached to an underground iron pipe helps prevent corrosion by being oxidized itself.



Galvanized object with zinc coating intact
The zinc coating seals the iron from air and water by forming a barrier of zinc oxide that repels water and oxygen.

Galvanized object with zinc coating broken
If the zinc coating breaks, the zinc acts as a sacrificial anode. The zinc coating, rather than the iron object, is oxidized.

Figure 17 Galvanization helps prevent corrosion in two ways.

Galvanization protects iron in two ways. When intact, the zinc layer prevents water and oxygen from reaching the iron's surface. When cracks form in the zinc, the zinc protects the iron by becoming the anode of the voltaic cell set up when water and oxygen contact iron and zinc, as shown in **Figure 17.**

Check Your Progress

Summary

- Primary batteries can be used only once; secondary batteries can be recharged.
- When a battery is recharged, electric energy supplied to the battery reverses the direction of the battery's spontaneous reaction.
- Fuel cells are batteries in which the substance oxidized is a fuel from an external source.
- Methods of preventing corrosion are painting, coating with another metal, or using a sacrificial anode.

Demonstrate Understanding

15. **Identify** what is reduced and what is oxidized in the zinc-carbon dry-cell battery. What features make the alkaline dry cell an improvement over the earlier type of dry-cell battery?
16. **Explain** what happens when a battery is recharged.
17. **Describe** the half-reactions that occur in a hydrogen fuel cell and write the equation for the overall reaction.
18. **Describe** the function of a sacrificial anode. How is the function of a sacrificial anode similar to galvanization?
19. **Explain** why lithium is a good choice for the anode of a battery.
20. **Calculate** Use data from **Table 1** to calculate the cell potential of the hydrogen-oxygen fuel cell.
21. **Design an Experiment** Use your knowledge of acids to devise a method for determining whether a lead-acid battery can deliver full charge or is beginning to run down.

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LESSON 3

ELECTROLYSIS

FOCUS QUESTION

How do electrolytic cells use energy to drive nonspontaneous reactions?

Reversing Redox Reactions

When a battery is connected in a circuit, electrons from the anode flow to the cathode, where they are used in a reduction reaction. How can a secondary battery be recharged? Compare the electrochemical cells in **Figure 18**. The beakers on the left contain zinc strips in solutions of zinc ions. The beakers on the right contain copper strips in solutions of copper ions. One electrochemical cell is supplying power to a light bulb by means of a spontaneous redox reaction. In this cell, electrons flow spontaneously from the zinc side to the copper side.

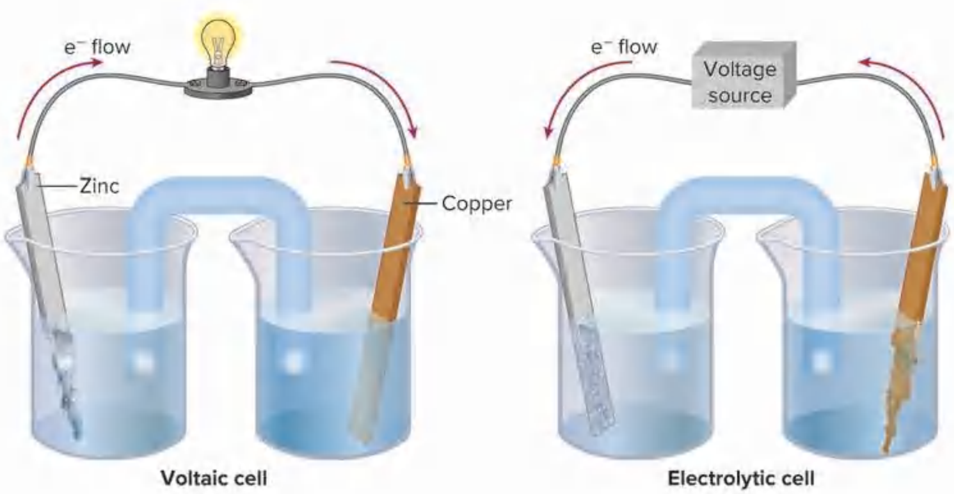


Figure 18 The zinc-copper electrochemical cell can be a voltaic cell or an electrolytic cell.
Infer *In each electrochemical cell, which metal is oxidized? What is reduced?*

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Laboratory: Electrolysis of Water
Analyze and interpret data to determine the effect of electric current passing through water.

Laboratory: Electroplating
Use mathematics and computational thinking to determine the cause and effect of mass lost by a copper anode and mass gained by a metal object being plated at the cathode.

The reaction continues until the zinc strip is used up, and then the reaction stops. However, the cell can be regenerated if current is applied in the reverse direction using an external voltage source. The voltage source is required because the reverse reaction is nonspontaneous. If the voltage source is applied long enough, the cell will return to nearly its original strength.

The use of electrical energy to bring about a chemical reaction is called **electrolysis.** An electrochemical cell in which electrolysis occurs is called an **electrolytic cell.** For example, when a secondary battery is recharged, it is acting as an electrolytic cell.

Applications of Electrolysis

Recall that voltaic cells convert chemical energy to electrical energy as a result of a spontaneous redox reaction. Electrolytic cells do the opposite; they use electrical energy to drive a nonspontaneous reaction. A common example is the electrolysis of water. This reaction is the opposite of consuming hydrogen and oxygen in a fuel cell.

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$$

The electrolysis of water is one method by which hydrogen gas can be generated for commercial use.

Electrolysis of molten NaCl

Just as electrolysis can decompose water into its elements, it can also separate molten sodium chloride into sodium metal and chlorine gas. This process is carried out in a chamber called a Down's cell, as illustrated in **Figure 19**. The electrolyte in the cell is the molten sodium chloride itself. Remember that ionic compounds can conduct electricity only when their ions are free to move, such as when they are dissolved in water or are in the molten state.

At the anode, chloride ions are oxidized to chlorine (Cl_2) gas.

$$2Cl^-(l) \rightarrow Cl_2(g) + 2e^-$$

At the cathode, sodium ions are reduced to sodium metal.

$$Na^+(l) + e^- \rightarrow Na(l)$$

The net cell reaction is the following.

$$2Na^+(l) + 2Cl^-(l) \rightarrow 2Na(l) + Cl_2(g)$$

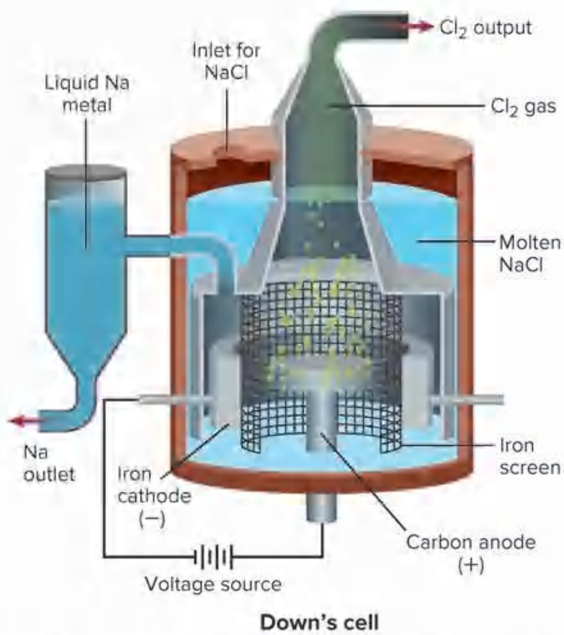
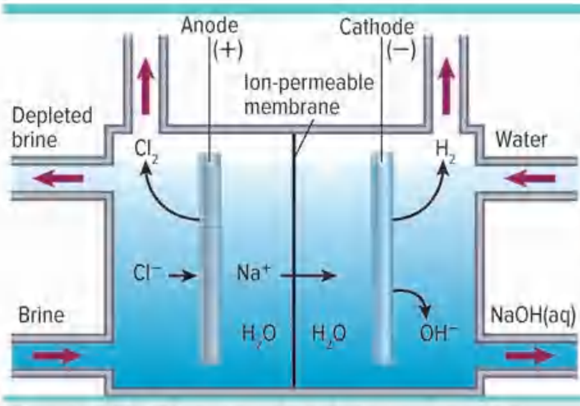


Figure 19 In a Down's cell, electrons supplied by a generator are used to reduce sodium ions at the cathode. As electrons are removed from the anode, chloride ions are oxidized at the anode to chlorine gas.

Get It?
Explain why the sodium chloride must be molten in the Down's cell.



Commercial facilities use an electrolytic process to obtain hydrogen gas, chlorine gas, and sodium hydroxide from brine.

Chlorine gas is used to manufacture polyvinyl chloride products, such as these pipes for water distribution.

Figure 20 In the electrolysis of brine (aqueous NaCl), sodium is not a product because water is easier to reduce.

Electrolysis of brine

The decomposition of brine, an aqueous solution of sodium chloride, is also carried out by means of electrolysis. **Figure 20** shows a typical electrolytic cell and the products of the electrolysis. Two reactions are possible at the cathode: the reduction of sodium ions and the reduction of hydrogen in water molecules.

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

$$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$$

However, the reduction of sodium (Na^+) does not occur because water is easier to reduce, and thus is reduced preferentially. Two reactions are also possible at the anode: the oxidation of chloride ions and the oxidation of oxygen in water molecules.

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

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$$

Because the desired product is chlorine (Cl_2), the concentration of chloride ions is kept high in order to favor this half-reaction. The overall cell reaction is as follows.

$$2H_2O(l) + 2NaCl(aq) \rightarrow H_2(g) + Cl_2(g) + 2NaOH(aq)$$

All three products are commercially important substances.

Get It?

Name the species that is oxidized and the species that is reduced in the electrolysis of brine.

SCIENCE USAGE v. COMMON USAGE

reduce

Science usage: to decrease an atom's oxidation number by the addition of electrons.

Zinc reduces copper(II) ions to copper atoms by releasing two electrons.

Common usage: to diminish in size, amount, extent, or number

The number of dancers had to be reduced because the stage was too small.

Aluminum production

Until the late nineteenth century, aluminum metal was more precious than gold because no one knew how to purify it in large quantities. In 1886, 22-year-old Charles Martin Hall (1863–1914) developed a process to produce aluminum by electrolysis. He used heat from a blacksmith forge, electricity from homemade batteries, and his mother's iron skillets as electrodes. At almost the same time, one of Le Châtelier's students, Paul L. T. Héroult (1863–1914), also 22 years old, discovered the same process. Today, it is called the Hall-Héroult process and is illustrated in **Figure 21**.

In the modern version of the Hall–Héroult process, aluminum metal is obtained by electrolysis of aluminum oxide, which is refined from bauxite ore. The aluminum oxide is dissolved at 1000°C in molten synthetic cryolite (Na_3AlF_6), another aluminum compound. The cell is lined with graphite, which forms the cathode for the reaction, as shown in **Figure 21**. Another set of graphite rods is immersed in the molten solution as an anode. The following half-reaction occurs at the cathode.

$$Al^{3+}(l) + 3e^- \rightarrow Al(l)$$

The molten aluminum settles to the bottom of the cell and is drawn off periodically. Oxide ions are oxidized at the cathode in this half-reaction.

$$2O^{2-}(aq) \rightarrow O_2(g) + 4e^-$$

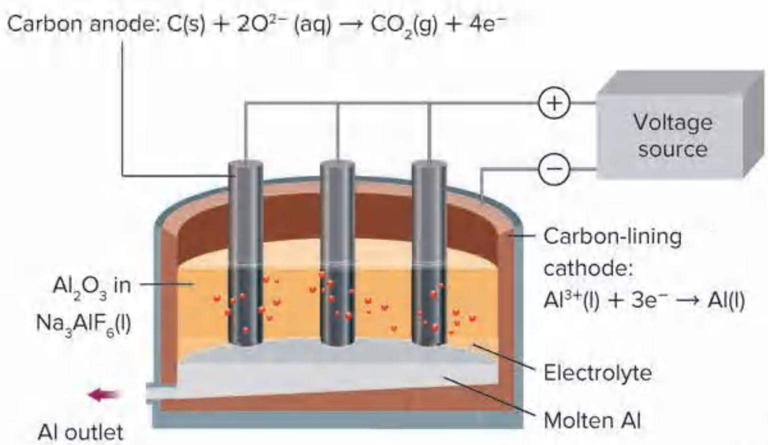
Because temperatures are high, the liberated oxygen reacts with the carbon of the anode to form carbon dioxide.

$$C(s) + O_2(g) \rightarrow CO_2(g)$$

Get It?

Analyze Why does the Hall–Héroult process need to be carried out at such high temperatures?

Figure 21 The Hall-Héroult process operates at temperatures over 900°C in smelters similar to this one. Note that carbon (graphite) serves as both the anode and the cathode. Recycled aluminum is often fed into the cell with the new aluminum.



Every ton of aluminum that is recycled saves huge quantities of electrical energy that would be used to produce new aluminum from ore.

The Hall–Héroult process uses huge amounts of electrical energy. For this reason, aluminum is often produced in plants built close to large hydroelectric power stations, where electrical energy is less expensive. The vast amount of electricity needed to produce aluminum from ore is the primary reason for recycling aluminum. Recycled aluminum has already undergone electrolysis, so the only energy required to make it usable again is the heat needed to melt it in a furnace.

Purification of ores

Electrolysis is also used in the purification of metals such as copper. Most copper is mined in the form of the ores chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), and malachite ($Cu_2CO_3(OH)_2$). The sulfides are most abundant and yield copper metal when heated strongly in the presence of oxygen.

$$Cu_2S(s) + O_2(g) \rightarrow 2Cu(l) + SO_2(g)$$

The copper obtained from this process contains many impurities and must be refined, so the molten copper is cast into large, thick plates. These plates are then used as an anode in an electrolytic cell containing a solution of copper(II) sulfate. The cathode of the cell is a thin sheet of pure copper. As current is passed through the cell, copper atoms in the impure anode are oxidized to copper(II) ions. The copper ions migrate through the solution to the cathode, where they are reduced to copper atoms. These atoms become part of the cathode, while any impurities fall to the bottom of the cell.

Electroplating

Objects are electroplated when a uniform coating is deposited usually as a protective or decorative layer. The substance used is typically a metal. Electroplating with a metal such as silver is accomplished with a method similar to that used to refine copper. The object to be silver-plated is the cathode of an electrolytic cell. The anode is a silver bar or sheet, as shown in **Figure 22**.

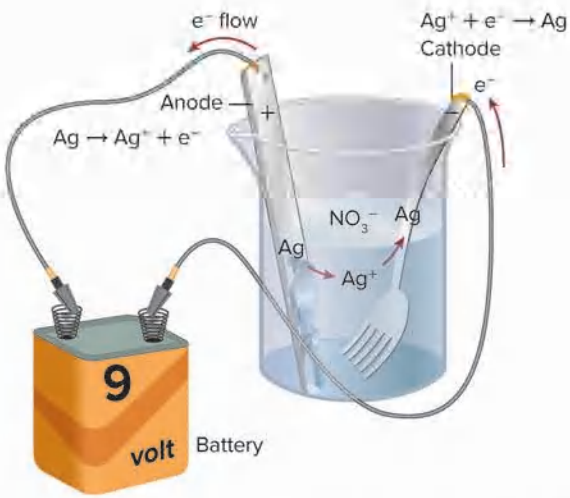


Figure 22 Power is needed to oxidize silver at the anode and reduce silver at the cathode. In an electrolytic cell used for silver plating, the object to be plated is the cathode where silver ions in the electrolyte solution are reduced to silver metal and deposited on the object.

Figure 23 A pen made of solid gold would be very expensive and heavy. Electroplating gold gives the same effect with a smaller mass and lower cost.

At the anode, silver is oxidized to silver ions as electrons are removed by the power source. At the cathode, the silver ions are reduced to silver metal by electrons from the external power source. The silver forms a thin coating over the object being plated. Current passing through the cell must be carefully controlled in order to get a smooth, even metal coating.

Other metals are also used for electroplating. For example, you might have seen items that are electroplated with gold, such as the pen shown in **Figure 23**. Exposed steel parts on bicycles and automobiles can be plated by nickel and then chrome to prevent corrosion.

Check Your Progress

Summary

- In an electrolytic cell, an outside source of power causes a nonspontaneous redox reaction to occur.
- The electrolysis of molten sodium chloride yields sodium metal and chlorine gas. The electrolysis of brine yields hydrogen gas, sodium hydroxide, and chlorine gas.
- Metals such as copper are purified in an electrolytic cell.
- Electrolysis is used to electroplate objects and to produce pure aluminum from its ore.

Demonstrate Understanding

22. **Define** electrolysis and relate the definition to the spontaneity of redox reactions.
23. **Explain** why the products of the electrolysis of brine and the electrolysis of molten sodium chloride are different.
24. **Describe** how impure copper obtained from the smelting of ore is purified by electrolysis.
25. **Explain,** by referring to the Hall–Héroult process, why recycling aluminum is very important.
26. **Describe** the anode and cathode of an electrolytic cell in which gold is to be plated on an object.
27. **Explain** why producing a kilogram of silver from its ions by electrolysis requires much less electric energy than producing a kilogram of aluminum from its ions.
28. **Calculate** Use Table 1 to calculate the voltage of the Down's cell. Should the potential be positive or negative?
29. **Summarize** Write a short paragraph answering each of the three Guiding Questions for Lesson 3 in your own words.

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STEM AT WORK

The Wide World of an Electrochemist

Electrochemists are scientists who study the production of electricity by chemical change and chemical change that is triggered by electric current. They might conduct experiments to study the effects of electricity on energy, chemical compounds, and devices, or they might be involved in developing technology and processes that use electrochemistry.

Photovoltaic cells, or solar cells, convert light energy into electricity. This is called photoelectrochemistry.

Developing Technologies that Solve Problems

The Electrochemical Society, a non-profit organization that has been supporting the study of electrochemistry for more than 100 years, calls electrochemistry a science that is "going to save the world." Electrochemists are playing a critical role in the development of more efficient and sustainable energy production and use. For example, technologies such as solar panels, fuel cells, and cars that run only on batteries all use electrochemistry and could increase the sustainability of our transportation and energy production systems.

Electrochemistry is also playing an important role in the burgeoning field of biosensors. Biosensors are devices used to analyze biological samples. Electrochemistry is used in biosensors that monitor blood glucose. This technology has improved the lives of people who have diabetes. The biosensors can be used to continuously monitor blood glucose levels, without the need for skin pricks. Biosensors that use electrochemistry have also been developed to detect salmonella in food. Electrochemistry is also used in breathalyzers, which are used to estimate the amount of alcohol in a person's breath and to prevent drunk driving.

USE A MODEL TO DESCRIBE

Choose a technology that uses electrochemistry. Research the electrochemistry involved in the technology. Summarize your findings in a visual model or graphic organizer of your own creation.

STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 VOLTAIC CELLS

- In a voltaic cell, oxidation and reduction take place at electrodes separated from each other.
- The standard potential of a half-cell reaction is its voltage when paired with a standard hydrogen electrode under standard conditions.
- The reduction potential of a half-cell is negative if it undergoes oxidation when connected to a standard hydrogen electrode. The reduction potential of a half-cell is positive if it undergoes reduction when connected to a standard hydrogen electrode.
- The standard potential of a voltaic cell is the difference between the standard reduction potentials of the half-cell reactions.

$$E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$$

Standard hydrogen electrode

- salt bridge
- electrochemical cell
- voltaic cell
- half-cell
- anode
- cathode
- reduction potential
- standard hydrogen electrode

STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 2 BATTERIES

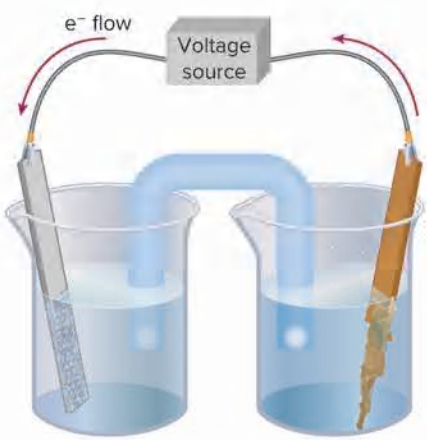
- Primary batteries can be used only once; secondary batteries can be recharged.
- When a battery is recharged, electric energy supplied to the battery reverses the direction of the battery's spontaneous reaction.
- Fuel cells are batteries in which the substance oxidized is a fuel from an external source.
- Methods of preventing corrosion are painting, coating with another metal, or using a sacrificial anode.

- battery
- dry cell
- primary battery
- secondary battery
- fuel cell
- corrosion
- galvanization

Lesson 3 ELECTROLYSIS

- In an electrolytic cell, an outside source of power causes a non-spontaneous redox reaction to occur.
- The electrolysis of molten sodium chloride yields sodium metal and chlorine gas. The electrolysis of brine yields hydrogen gas, sodium hydroxide, and chlorine gas.
- Metals such as copper are purified in an electrolytic cell.
- Electrolysis is used to electroplate objects and to produce pure aluminum from its ore.

- electrolysis
- electrolytic cell



Electrolytic cell

THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

Where do cameras get their power?

CER Claim, Evidence, Reasoning

Explain Your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will apply your evidence from this module and complete your project.

GO FURTHER

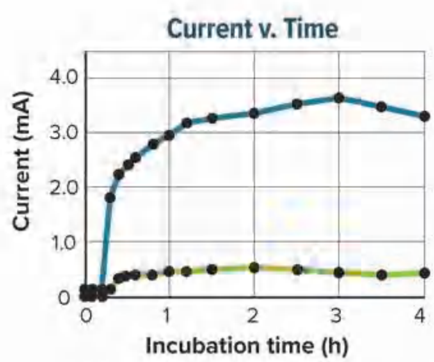
Based on Real Data*

SEP Data Analysis Lab

How can you get electric current from microbes?

Scientists have studied the use of biofuel cells to convert microbial metabolic energy into electric current. An electron mediator, which taps into the electron transport chain of cells and steals the electrons that are produced, facilitates transfer of electrons to an electrode.

Data and Observations The graph shows the current produced in a biofuel cell with (blue line) and without (green line) the use of an electron mediator.



*Data obtained from: Hyun Park, Doo and J. Gregory Zeikus. April, 2000. Electricity Generation in Microbial Fuel Cells Using Neutral Red as an Electronophore. Applied and Environmental Microbiology 66, No. 4:1292–1297.

CER Analyze and Interpret Data

1. **Infer** the approximate time when the electron mediator was introduced.
2. **Claim, Evidence, Reasoning** Did the introduction of the electron mediator make a difference in the current production? Explain.

HYDROCARBONS

ENCOUNTER THE PHENOMENON

What is fueling this natural fire?

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

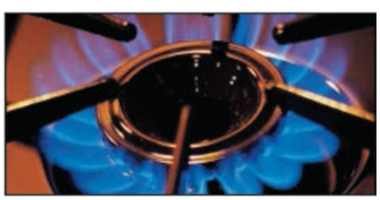
CER Claim, Evidence, Reasoning

Make Your Claim Use your CER chart to make a claim about what is fueling this natural fire.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.



LESSON 1: Explore & Explain: Hydrocarbons

LESSON 2: Explore & Explain: Properties of Alkanes

LESSON 1

INTRODUCTION TO HYDROCARBONS

FOCUS QUESTION

What are hydrocarbons and how are they used?

Organic Compounds

Chemists in the early nineteenth century knew that living things, such as the plants and panda shown in **Figure 1**, produce an immense variety of carbon compounds. Chemists referred to these compounds as *organic* compounds because they were produced by living organisms. Scientists at this time felt that all organic compounds came only from living things.

Once Dalton's atomic theory was accepted, chemists began to understand that compounds, including those made by living organisms, consisted of arrangements of atoms bonded together in certain combinations. They were able to synthesize many new and useful substances. However, scientists were not able to synthesize organic compounds. Many scientists incorrectly concluded that they were unable to synthesize organic compounds because of vitalism. According to vitalism, organisms possessed a mysterious "vital force," enabling them to assemble carbon compounds.

Disproving vitalism

Friedrich Wöhler (1800–1882), a German chemist, was the first scientist to realize that he had produced an organic compound, called urea, by synthesis in a laboratory. Wöhler's experiment did not immediately disprove vitalism, but it prompted a chain of similar experiments by other European chemists. Eventually, the idea that the synthesis of organic compounds required a vital force was discredited and scientists realized they could synthesize organic compounds in the laboratory.

Figure 1 Living things contain, are made up of, and produce a variety of organic compounds. Identify two organic compounds that you have studied in a previous science course.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practices: Bonding and Reactions of Carbon Compounds

HS-PS1-1. Use the periodic table as a model to predict the relative properties of elements based on patterns of electrons in the outermost energy level of atoms.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the module question?

Organic chemistry

Today, the term **organic compound** is applied to all carbon-containing compounds with the primary exceptions of carbon oxides, carbides, and carbonates, which are considered inorganic. Because there are so many organic compounds, an entire branch of chemistry, called organic chemistry, is devoted to their study. Recall that carbon is an element in group 14 of the periodic table, as shown in **Figure 2.** With the electron configuration of $1s^22s^22p^2$, carbon nearly always shares its electrons and forms four covalent bonds. In organic compounds, carbon atoms are bonded to hydrogen atoms or atoms of other elements that are near carbon in the periodic table—especially nitrogen, oxygen, sulfur, phosphorus, and the halogens.

Most importantly, carbon atoms also bond to other carbon atoms and form chains from two to thousands of carbon atoms in length. Also, because carbon forms four bonds, it forms complex, branched-chain structures, ring structures, and even cagelike structures. With all of these bonding possibilities, chemists have identified millions of different organic compounds and are synthesizing more every day.

Some of these new organic compounds are used in the medical field. Constant research and development into new medications generates new organic molecules that are developed to help humans live longer, healthier lives.

Get It?
Explain why carbon forms many compounds.

Figure 2 Carbon can bond to four other elements and form thousands of different compounds.

Hydrocarbons

The simplest organic compounds are **hydrocarbons,** which contain only the elements carbon and hydrogen. How many different compounds do you think two elements can form? You might guess that only a few compounds are possible. However, thousands of hydrocarbons are known, each containing only the elements carbon and hydrogen. The simplest hydrocarbon molecule, CH_4, consists of a carbon atom bonded to four hydrogen atoms. This substance, called methane, is an excellent fuel and is the main component of natural gas, shown in **Figure 3.**

Figure 3 Methane is a hydrocarbon found in natural gas. It is the simplest hydrocarbon.

Identify *In addition to hydrogen, what other elements readily bond with carbon?*

Get It?
Name two uses of methane or natural gas in your home or community.

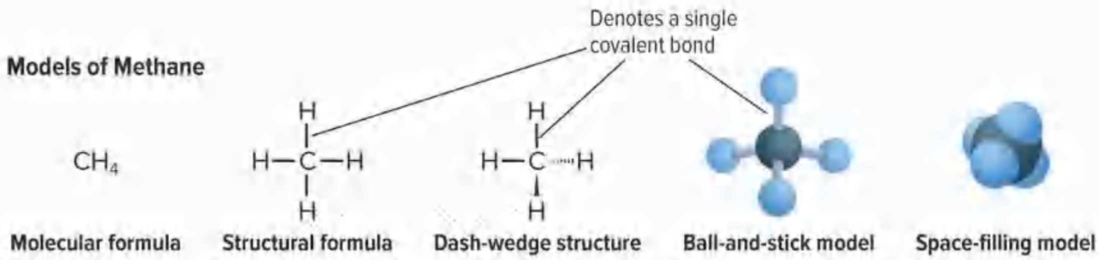


Figure 4 Chemists use four different models to represent a methane (CH_4) molecule. See the Reference Tables in the Student Resources for a key to atom color conventions.

Models and hydrocarbons

Chemists represent organic molecules in a variety of ways. **Figure 4** shows four different ways to represent a methane molecule. Covalent bonds are represented by a single straight line, which denotes two shared electrons. Most often, chemists use the type of model that best shows the information they want to highlight. As shown in **Figure 4,** molecular formulas give no information about the geometry of the molecule. A structural formula shows the general arrangement of atoms in the molecule but not the exact, three-dimensional geometry. The ball-and-stick model demonstrates the geometry of the molecule clearly, but the space-filling model gives a more realistic picture of what a molecule would look like if you could see it. Keep in mind as you look at the models that the atoms are held closely together by electron-sharing bonds.

Multiple carbon-carbon bonds

Carbon atoms can bond to each other not only by single covalent bonds but also by double and triple covalent bonds, as shown in **Figure 5.** Recall that in a double bond, the two atoms in the bond share two pairs of electrons; in a triple bond, they share three pairs of electrons.

In the nineteenth century, before chemists understood the structure of organic substances, they experimented with hydrocarbons that were obtained from heating animal fats and plant oils. They classified these hydrocarbons according to a simple chemical test in which they mixed each hydrocarbon compound with a bromine solution and then measured how much bromine reacted with the hydrocarbon. They found that some of the hydrocarbons would react with a small amount of bromine, some would react with more, and some would not react with any amount of bromine. Chemists called the hydrocarbons that reacted with bromine unsaturated hydrocarbons in the same sense that an unsaturated aqueous solution can dissolve more solute. Hydrocarbons that did not react with bromine were said to be saturated. Again, similar to aqueous solutions where a saturated solution is a solution in which no more solute can dissolve, a saturated hydrocarbon did not react with any of the bromine.

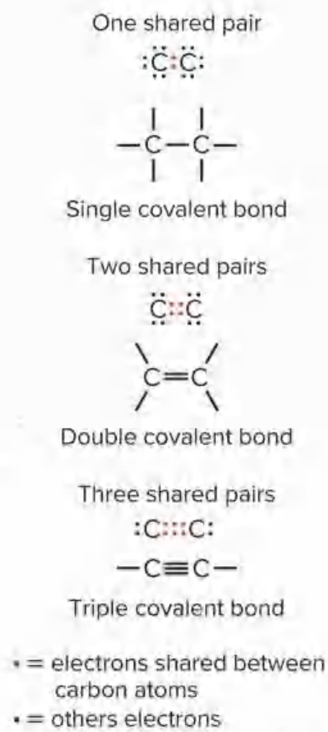


Figure 5 Carbon can bond to other carbon atoms in double and triple bonds. These Lewis structures and structural formulas show two ways to denote double and triple bonds.

Present-day chemists can now explain the experimental results obtained 170 years ago. Hydrocarbons that reacted with bromine had double or triple covalent bonds. The bromine is substituted into the molecule, turning all bonds to single bonds. Those compounds that did not react with bromine had only single covalent bonds. Today, a hydrocarbon having only single bonds is defined as a **saturated hydrocarbon.** A hydrocarbon that has at least one double or triple bond between carbon atoms is an **unsaturated hydrocarbon.**

Get It?

Explain the origin of the terms *saturated* and *unsaturated hydrocarbons*.

Refining Hydrocarbons

Today, many hydrocarbons are obtained from a fossil fuel called petroleum. Petroleum formed from the remains of microorganisms that lived in Earth's oceans millions of years ago. Over time, the remains formed thick layers of mud-like deposits on the ocean floor. Heat from Earth's interior and the tremendous pressure of overlying sediments transformed this mud into oil-rich shale and natural gas. In certain kinds of geological formations, the petroleum ran out of the shale and collected in pools deep in Earth's crust. Natural gas, which formed at the same time and in the same way as petroleum, is usually found with petroleum deposits. Natural gas is composed primarily of methane, but it also contains small amounts of other hydrocarbons that have from two to five carbon atoms.

Fractional distillation

Unlike natural gas, petroleum is a complex mixture containing more than a thousand different compounds. For this reason, raw petroleum, sometimes called crude oil, has little practical use. Petroleum is much more useful to humans when it is separated into simpler components or fractions. Separation is carried out in a process called **fractional distillation,** also called fractionation, which involves boiling the petroleum and collecting components or fractions as they condense at different temperatures. Fractional distillation is done in a fractionating tower similar to the one shown in **Figure 6** on the next page.

The temperature inside the fractionating tower is controlled so that it remains near 400°C at the bottom, where the petroleum is boiling, and gradually decreases toward the top. The condensation temperatures (boiling points) generally decrease as molecular mass decreases. Therefore, as the vapors travel up through the column, the hydrocarbons condense and are drawn off, as shown in **Figure 6.**

SCIENCE USAGE v. COMMON USAGE

deposit

Science usage: a natural collection of oil or ore

There was a rich deposit of copper in the mountain.

Common usage: money placed into a bank account or the act of placing money in a bank account

The store owner placed his deposit in the after-hours slot at the bank.

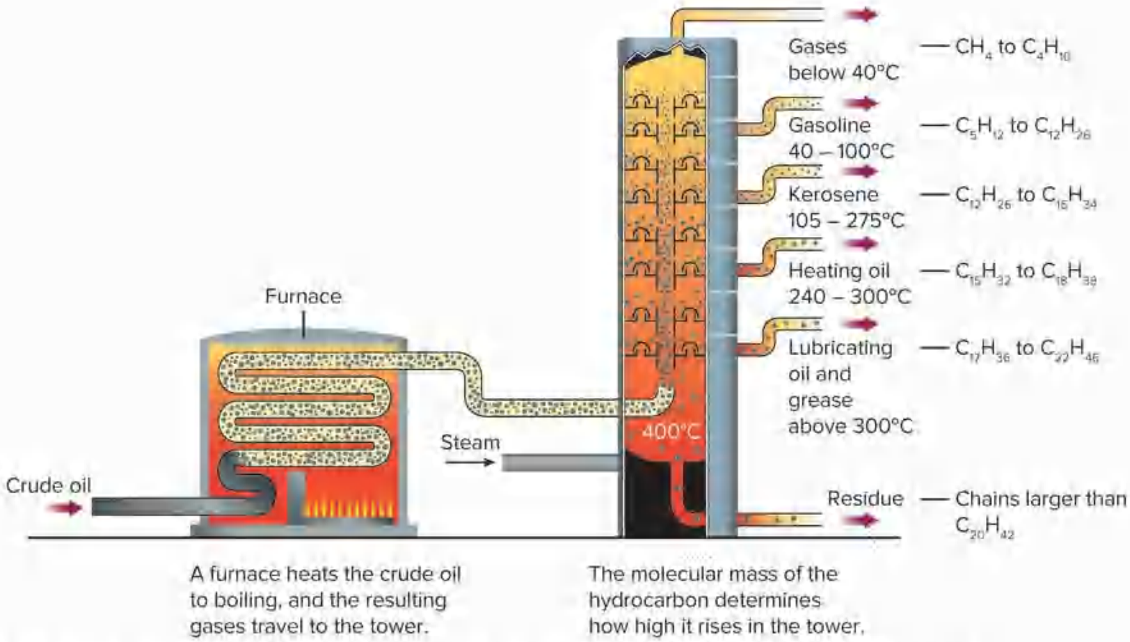


Figure 6 This diagram of a fractional tower shows that fractions with lower boiling points, such as gasoline and gaseous products, are drawn off in the cooler regions near the top of the tower. Oils and greases, having much higher boiling points, stay near the bottom of the tower and are drawn off there.

Figure 6 also gives the names of the typical fractions separated from petroleum, along with their boiling points, hydrocarbon size ranges, and common uses. You might recognize some of the fractions because you use them every day. Unfortunately, fractional distillation towers, shown in **Figure 7,** do not yield fractions in the same proportions that they are needed. For example, distillation seldom yields the amount of gasoline desired. However, it yields more of the heavier oils than the market demands.

Many years ago, petroleum chemists and engineers developed a process to help match the supply with the demand. This process in which heavier fractions are converted to gasoline by breaking their large molecules into smaller molecules is called **cracking.** Cracking is done in the absence of oxygen and in the presence of a catalyst. In addition to breaking heavier hydrocarbons into molecules of the size range needed for gasoline, cracking also produces starting materials for the synthesis of many different products, including plastic products, films, and synthetic fabrics.

Get It?

Infer *What types of emissions must be controlled to protect the environment?*

Figure 7 Fractional distillation towers separate large quantities of petroleum into usable components. Thousands of products we use in our homes, for transportation, and in industry result from petroleum refining.

Rating gasoline

None of the petroleum fractions is a pure substance. As shown in **Figure 6,** gasoline is not a pure substance, but rather a mixture of hydrocarbons. Most molecules with single covalent bonds in gasoline have 5 to 12 carbon atoms. However, the gasoline pumped into cars today is different from the gasoline used in automobiles in the early 1900s. The gasoline fraction that is distilled from petroleum is modified by adjusting its composition and adding substances to improve its performance in today's automobile engines and to reduce pollution from car exhaust.

It is critical that the gasoline-air mixture in the cylinder of an automobile engine ignite at exactly the right instant and burn evenly. If it ignites too early or too late, much energy will be wasted, fuel efficiency will drop, and the engine will wear out prematurely. Most straight-chain hydrocarbons burn unevenly and tend to ignite from heat and pressure before the piston is in the proper position and the spark plug fires. This early ignition causes a rattling or pinging noise called knocking.

In the late 1920s, an antiknock, or octane rating, system for gasoline was established, resulting in the octane ratings posted on gasoline pumps like those shown in **Figure 8.** Mid-grade gasoline today has a rating of about 89, whereas premium gasoline has ratings of 91 or higher. Several factors determine which octane rating a car needs, including how much the piston compresses the air-fuel mixture and the altitude at which the car is driven.

It is not recommended that a lower than specified octane gasoline be used in an engine. This can lead to reduced fuel economy as the computer in the vehicle adjusts to maximize performance with the fuel available to the engine. If a car does not require a premium gas, there is really no added advantage to using a premium gasoline.

Figure 8 Octane ratings are used to give the antiknock rating of the fuel. Mid-grade gasoline for cars has an octane rating of about 89. Aviation fuel has an octane rating of about 100. Racing fuel has an octane rating of about 110.

Get It?

Explain why the lead that was added to gasoline to prevent knocking from the 1920's to the 1970's is no longer used as an additive in gasoline in North America.

EARTH SCIENCE Connection Since ancient times, people have found petroleum seeping from cracks in rocks. Historical records show that petroleum has been used for more than 5000 years. In the nineteenth century, as the United States entered the machine age and its population increased, the demand for petroleum products, namely kerosene for lighting and lubricants for machines, increased. In an attempt to find a reliable petroleum supply, Edwin Drake drilled the first oil well in the United States in Pennsylvania, in 1859. The oil industry flourished for a time, but when Thomas Edison introduced the electric light in 1882, investors feared that the industry was doomed. However, the invention of the automobile in the 1890s revived the industry on a massive scale.

Today, much of the crude oil production in the United States occurs in Oklahoma, North Dakota, California, Alaska, and Texas. The crude oil must be refined before it can be used. Crude oil is send to refineries located in many states in the United States. The states with the greatest number of refineries are Texas, California, Oklahoma, Tennessee and Louisiana. Once refined, the products are then sent out to various industries in need of the refined products.

Several pipeline projects are being suggested that could help move crude oil and its refined products throughout North America. The debates over public safety and whether or not these pipelines should be constructed continues today.

Check Your Progress

Summary

- Organic compounds contain carbon, which is able to form straight chains and branched chains.
- Hydrocarbons are organic substances composed of carbon and hydrogen.
- The major sources of hydrocarbons are petroleum and natural gas.
- Petroleum can be separated into components by the process of fractional distillation.

Demonstrate Understanding

1. **Identify** three applications of hydrocarbons as a source of energy and raw materials.
2. **Name** an organic compound and explain what an organic chemist studies.
3. **Describe** what each of the four molecular models highlights about a molecule.
4. **Compare and contrast** saturated and unsaturated hydrocarbons.
5. **Describe** the process of fractional distillation.
6. **Infer** Some shortening products are described as "hydrogenated vegetable oil", which are oils that react with hydrogen in the presence of a catalyst. Form a hypothesis to explain why hydrogen reacted with the oils.
7. **Interpret Data** Refer to **Figure 6.** What property of hydrocarbon molecules correlates to the viscosity of a particular fraction when it is cooled to room temperature?

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LESSON 2
ALKANES

FOCUS QUESTION

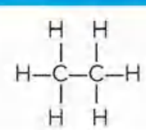
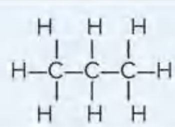
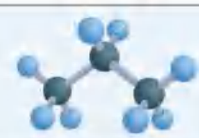
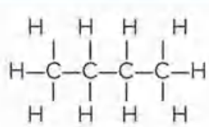
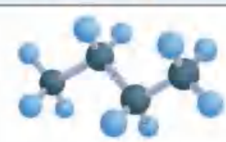
What are the properties of hydrocarbons with a single bond?

Straight-Chain Alkanes

Methane is the smallest member of a series of hydrocarbons known as alkanes. It is used as a fuel and is a product of many biological processes. **Alkanes** are hydrocarbons that have only single bonds between atoms. The models for ethane (C_2H_6), the second member of the alkane series, are shown in **Table 1.** Ethane consists of two carbon atoms bonded together with a single bond and six hydrogen atoms sharing the remaining valence electrons of the carbon atoms.

The third member of the alkane series, propane, has three carbon atoms and eight hydrogen atoms, giving it the molecular formula C_3H_8. The next member, butane, has four carbon atoms and the formula C_4H_{10}. Compare the structures of ethane, propane, and butane in **Table 1.**

Table 1 Simple Alkanes

Molecular Formula	Structural Formula	Ball-and-Stick Model	Space-Filling Model
Ethane (C_2H_6)			
Propane (C_3H_8)			
Butane (C_4H_{10})			

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

ChemLAB: Analyze Hydrocarbon Burner Gases

Plan and carry out an investigation to determine the structure and function of the alkane gas used in laboratory.

Laboratory: The Ripening of Fruit with Ethene

Develop an investigation to examine the effect of fruit ripening in an open or closed system.

Table 2 First Ten of the Alkane Series

Name	Molecular Formula	Condensed Structural Formula
Methane	CH_4	CH_4
Ethane	C_2H_6	CH_3CH_3
Propane	C_3H_8	$CH_3CH_2CH_3$
Butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$
Pentane	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$
Hexane	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$
Heptane	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
Octane	C_8H_{18}	$CH_3(CH_2)_6CH_3$
Nonane	C_9H_{20}	$CH_3(CH_2)_7CH_3$
Decane	$C_{10}H_{22}$	$CH_3(CH_2)_8CH_3$

Naming straight-chain alkanes

Notice that names of alkanes end in *-ane.* Also, alkanes with five or more carbons in a chain have names that use a prefix derived from the Greek or Latin word for the number of carbons in each chain. For example, *pent*ane has five carbons just as a *pent*agon has five sides, and *oct*ane has eight carbons. Because methane, ethane, propane, and butane were named before alkane structures were known, their names do not have numerical prefixes. **Table 2** shows the names and structures of the first ten alkanes. Notice the underlined prefix representing the number of carbon atoms in the molecule.

In **Table 2,** you can see that the structural formulas are written in a different way from those in **Table 1.** These condensed structural formulas save space by not showing the hydrogen atoms off of the carbon atoms. Condensed formulas can be written in several ways. In **Table 2,** the lines between carbon atoms have been eliminated to save space.

In **Table 2,** you can see that $-CH_2-$ is a repeating unit in the chain of carbon atoms. Note, for example, that pentane has one more $-CH_2-$ unit than butane. You can further condense structural formulas by writing the $-CH_2-$ unit in parentheses followed by a subscript to show the number of units, as is done with octane, nonane, and decane.

A series of compounds that differ from one another by a repeating unit is called a **homologous series.** A homologous series has a fixed numerical relationship among the numbers of atoms. For alkanes, the relationship between the numbers of carbon and hydrogen atoms can be expressed as C_nH_{2n+2}, where n is equal to the number of carbon atoms in the alkane. Given the number of carbon atoms in an alkane, you can write the molecular formula for any alkane. For example, heptane has seven carbon atoms, so its formula is $C_7H_{2(7)+2}$, or C_7H_{16}.

Get It?

Write the molecular formula for an alkane that has 13 carbon atoms in its molecular structure.

Branched Chain Alkanes

The alkanes discussed so far in this chapter are called straight-chain alkanes because the carbon atoms are bonded to each other in a single line. Now look at the two structures in **Figure 9.** If you count the carbon and hydrogen atoms, you will discover that both structures have the same molecular formula, C_4H_{10}. The structure on the left represents butane, and the structure on the right represents a branched-chain alkane known as isobutane—a substance whose chemical and physical properties are different from those of butane. Carbon atoms can bond to one, two, three, or even four other carbon atoms. This property makes possible a variety of branched-chain alkanes.

Both butane and isobutane are used as raw materials for many chemical processes and applications, as shown in **Figure 9.**

Get It?

Describe the difference in the molecular structures of butane and isobutane.

Alkyl groups

You have seen that both a straight-chain and a branched-chain alkane can have the same molecular formula. While the molecular formulas are the same, their structural arrangements are different. This fact illustrates a basic principle of organic chemistry: the order and arrangement of atoms in an organic molecule determine its identity. Therefore, the name of an organic compound must also accurately describe the molecular structure of the compound.

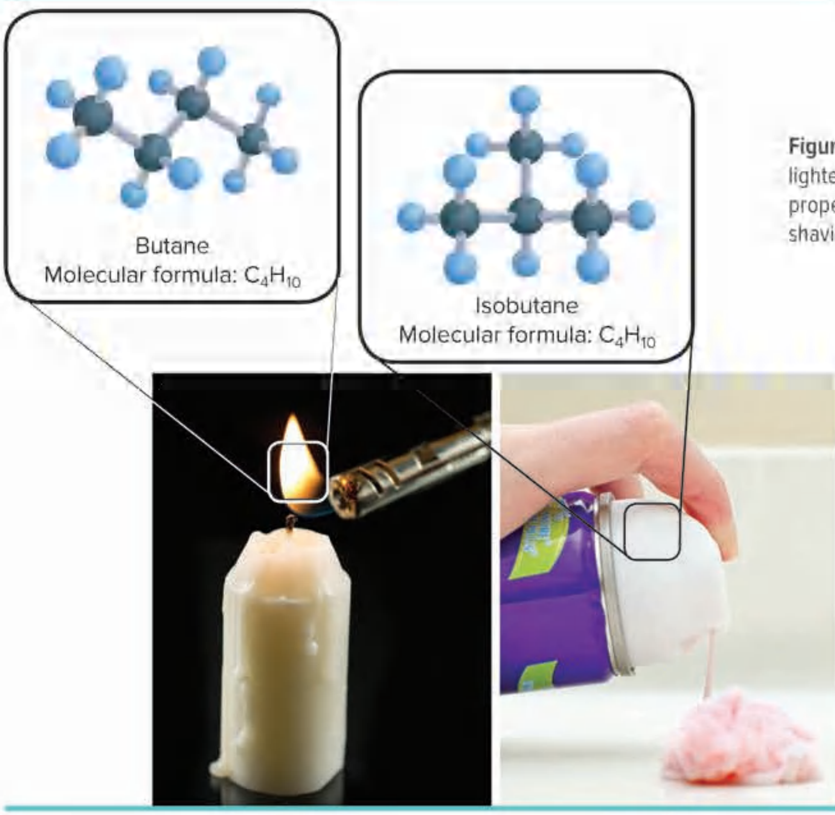
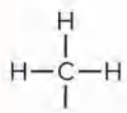
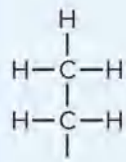
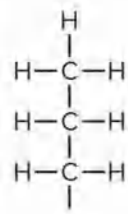
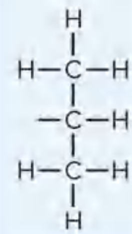
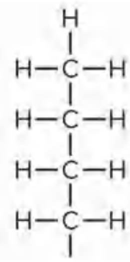


Figure 9 Butane is a fuel used in lighters. Isobutane is used as a propellant in products such as shaving gel.

Table 3 Common Alkyl Groups

Name	Methyl	Ethyl	Propyl	Isopropyl	Butyl
Condensed structural formula	$CH_3—$	$CH_3CH_2—$	$CH_3CH_2CH_2—$	CH_3CHCH_3	$CH_3CH_2CH_2CH_2—$
Structural formula					

When naming branched-chain alkanes, the longest continuous chain of carbon atoms is called the **parent chain.** All side branches are called **substituent groups** because they appear to substitute for a hydrogen atom in the straight chain. Each alkane-based substituent group branching from the parent chain is named for the straight-chain alkane that has the same number of carbon atoms as the substituent. The ending *-ane* is replaced with the letters *-yl.* An alkane-based substituent group is called an alkyl group. Several alkyl groups are shown in **Table 3.**

Naming branched-chain alkanes

To name organic structures, chemists use the following systematic rules approved by the International Union of Pure and Applied Chemistry (IUPAC).

Step 1. *Count the number of carbon atoms in the longest continuous chain.* Use the name of the straight-chain alkane with that number of carbons as the name of the parent chain of the structure.

Step 2. *Number each carbon in the parent chain.* Locate the end carbon closest to a substituent group. Label that carbon *Position 1.* This step gives all the substituent groups the lowest position numbers possible.

Step 3. *Name each alkyl group substituent.* Place the name of the group before the name of the parent chain.

Step 4. *If the same alkyl group occurs more than once as a branch on the parent structure, use a prefix* (di-, tri-, tetra-, *and so on*) *before its name to indicate how many times it appears.*

ACADEMIC VOCABULARY

substitute

a person or thing that takes the place of another

A substitute teacher taught chemistry class yesterday.

Then, use the number of the carbon to which each is attached to indicate its position.

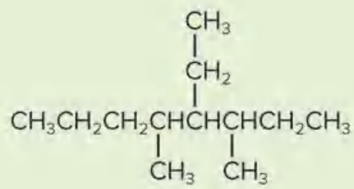
Step 5. *When different alkyl groups are attached to the same parent structure, place their names in alphabetical order.* Do not consider the prefixes (*di-*, *tri-*, and so on) when determining alphabetical order.

Step 6. *Write the entire name, using hyphens to separate numbers from words and commas to separate numbers.* Do not add a space between the substituent name and the name of the parent chain.

EXAMPLE Problem 1

NAMING BRANCHED-CHAIN ALKANES

Name the alkane shown.

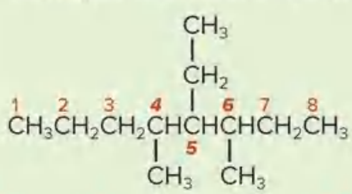


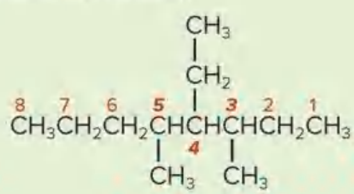
1 ANALYZE THE PROBLEM

You are given a structure. To determine the name of the parent chain and the names and locations of branches, follow the IUPAC rules.

2 SOLVE FOR THE UNKNOWN

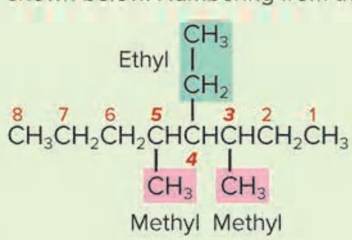
Step 1. *Count the number of carbon atoms in the longest continuous chain.* Because structural formulas can be written with chains oriented in various ways, you need to be careful in finding the longest continuous carbon chain. In this case, it is easy.





The longest chain has eight carbon atoms, so the parent name is *octane*.

Step 2. *Number each carbon in the parent chain.* Number the chain in both directions, as shown below. Numbering from the left puts the alkyl groups at Positions 4, 5, and 6.



Numbering from the right puts alkyl groups at positions 3, 4, and 5. Because 3, 4, and 5 are the lowest position numbers, they will be used in the name.

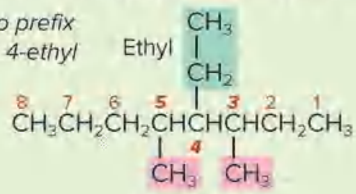
EXAMPLE Problem 1 (continued)

Step 3. *Name each alkyl group substituent.* Identify and name the alkyl groups branching from the parent chain. There are one-carbon methyl groups at Positions 3 and 5, and a two-carbon ethyl group at Position 4.

Step 4. *If the same alkyl group occurs more than once as a branch on the parent structure, use a prefix* (*di-, tri-, tetra-, and* so on) *before its name to indicate how many times it appears.* Look for and count the alkyl groups that occur more than once. Determine the prefix to use to show the number of times each group appears. In this example, the prefix *di-* will be added to the name *methyl* because two methyl groups are present. No prefix is needed for the one ethyl group. Then show the position of each group with the appropriate number.

One ethyl group: *no prefix*
Position and name: *4-ethyl*

Ethyl



Parent chain: *octane*

Methyl Methyl

Two methyl groups: use *dimethyl*
Position and name: *3,5-dimethyl*

Step 5. *Whenever different alkyl groups are attached to the same parent structure, place their names in alphabetical order.* Place the names of the alkyl branches in alphabetical order, ignoring the prefixes. Alphabetical order puts the name *ethyl* before *dimethyl*.

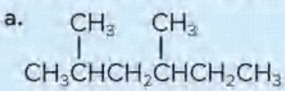
Step 6. *Write the entire name, using hyphens to separate numbers from words and commas to separate numbers.* Write the name of the structure, using hyphens and commas as needed. The name should be written as *4-ethyl-3,5-dimethyloctane.*

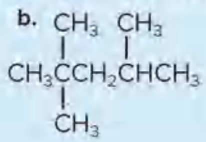
3 EVALUATE THE ANSWER

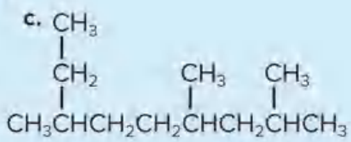
The longest continuous carbon chain has been found and numbered correctly. All branches have been designated with correct prefixes and alkyl group names. Alphabetical order and punctuation are correct.

PRACTICE Problems ADDITIONAL PRACTICE

8. Use the IUPAC rules to name the following structures.

a. 

b. 

c. 

9. CHALLENGE Draw the structures of the following branched-chain alkanes.

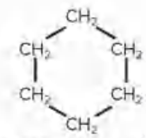
a. 2,3-dimethyl-5-propyldecane

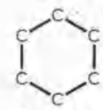
b. 3,4,5-triethyloctane

Cycloalkanes

One of the reasons that such a variety of organic compounds exists is that carbon atoms can form ring structures. An organic compound that contains a hydrocarbon ring is called a **cyclic hydrocarbon.** To indicate that a hydrocarbon has a ring structure, the prefix *cyclo-* is used with the hydrocarbon name. Thus, cyclic hydrocarbons that contain only single bonds are called **cycloalkanes.**

Cycloalkanes can have rings with three, four, five, six, or even more carbon atoms. The name for the six-carbon cycloalkane is *cyclohexane*. Cyclohexane, which is obtained from petroleum, is used in paint and varnish removers and for extracting essential oils to make perfume. Note that cyclohexane (C_6H_{12}) has two fewer hydrogen atoms than straight-chain hexane (C_6H_{14}) because a valence electron from each of two carbon atoms is now forming a carbon-carbon bond rather than a carbon-hydrogen bond.


Condensed structural formula


Skeletal structure


Line structure

Figure 10 Cyclohexane can be represented in several ways.

Get It?

Evaluate If the prefix *cyclo-* is present in the name of an alkane, what do you know about the alkane?

As shown in **Figure 10,** cyclic hydrocarbons such as cyclohexane are represented by condensed, skeletal, and line structures. Line structures show only the carbon-carbon bonds with carbon atoms understood to be at each vertex of the structure. Hydrogen atoms are assumed to occupy the remaining bonding positions unless substituents are present. Hydrogen atoms are also not shown in the skeletal structures for hydrocarbons.

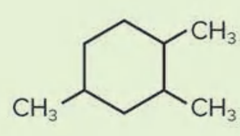
Naming substituted cycloalkanes

Like other alkanes, cycloalkanes can have substituent groups. Substituted cycloalkanes are named by following the same IUPAC rules used for straight-chain alkanes, but with a few modifications. With cycloalkanes, there is no need to find the longest chain because the ring is always considered to be the parent chain. Because a cyclic structure has no ends, numbering is started on the carbon that is bonded to the substituent group. When there are two or more substituents, the carbons are numbered around the ring in a way that gives the lowest-possible set of numbers for the substituents. If only one group is attached to the ring, no number is necessary, as this group is understood to be attached to the carbon that would be numbered as carbon 1. The following Example Problem illustrates the naming process for cycloalkanes.

EXAMPLE Problem 2

NAMING CYCLOALKANES

Name the cycloalkane shown.



1 ANALYZE THE PROBLEM

You are given a structure. To determine the parent cyclic structure and the location of branches, follow the IUPAC rules.

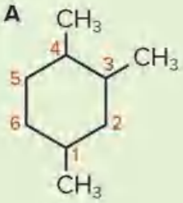
EXAMPLE Problem 2 (continued)

2 SOLVE FOR THE UNKNOWN

Step 1. Count the carbons in the ring, and use the name of the parent cyclic hydrocarbon. In this case, the ring has six carbons, so the parent name is *cyclohexane*.

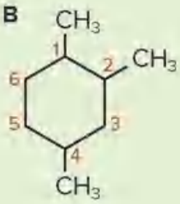
Step 2. Number the ring, starting from one of the CH_3— branches. Find the numbering that gives the lowest possible set of numbers for the branches. Here are two ways of numbering the ring.

A



1,3,4

B



1,2,4

Numbering from the carbon atom at the bottom of the ring puts the CH_3— groups at Positions 1, 3, and 4 in Structure A. Numbering from the carbon at the top of the ring gives Positions 1, 2, and 4. All other numbering schemes place the CH_3— groups at higher position numbers. Thus, 1, 2, and 4 are the lowest possible position numbers and will be used in the name.

Step 3. Name the substituents. All three are the same—carbon methyl groups.

Step 4. Add the prefix to show the number of groups present. Three methyl groups are present, so you add the prefix *tri-* to the name *methyl* to make *trimethyl*.

Step 5. Alphabetical order can be ignored because only one type of group is present.

Step 6. Put the name together using the name of the parent cycloalkane. Use commas between separate numbers, and hyphens between numbers and words. Write the name as *1,2,4-trimethylcyclohexane*.

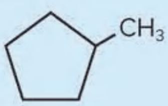
3 EVALUATE THE ANSWER

The parent-ring structure is numbered to give the branches the lowest possible set of numbers. The prefix *tri-* indicates that three methyl groups are present. No alphabetization is necessary because all branches are methyl groups.

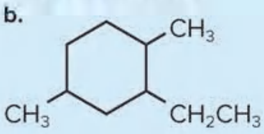
PRACTICE Problems **ADDITIONAL PRACTICE**

10. Use IUPAC rules to name the following structures.

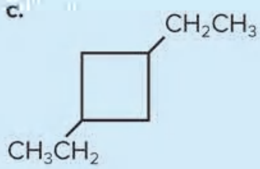
a.



b.



c.



11. CHALLENGE Draw the structures of the following cycloalkanes.

a. 1-ethyl-3-propylcyclopentane

b. 1,2,2,4-tetramethylcyclohexane

Figure 11 Many solvents–used as thinners for paint, coatings, waxes, photocopier toners, adhesives, and printer press inks–contain alkanes and cycloalkanes.

Properties of Alkanes

You have learned that the structure of a molecule affects its properties. For example, the O–H bonds in a water molecule are polar, and because the H–O–H molecule has a bent geometry, the molecule itself is polar. Thus, water molecules can form hydrogen bonds with each other. As a result, the boiling and melting points of water are much higher than those of other substances having similar molecular mass and size.

What properties would you predict for alkanes? All of the bonds in alkanes are between either a carbon atom and a hydrogen atom or between two carbon atoms. A bond between two identical atoms, such as carbon, can never be polar. Also, the C–H bonds have only a small electronegativity difference and are nonpolar. Because all of the bonds in alkanes are nonpolar, alkane molecules are nonpolar, which makes them good solvents for other nonpolar substances, as shown in **Figure 11.**

Physical properties of alkanes

How do the properties of a polar and nonpolar compound compare? Refer to **Table 4,** and note that the molecular mass of methane (16 amu) is close to the molecular mass of water (18 amu). Also, water and methane molecules are similar in size. However, when you compare the melting and boiling points of methane to those of water, you can see evidence that the molecules differ in some significant way. These temperatures differ greatly because methane molecules have little intermolecular attraction compared to water molecules. This difference in attraction can be explained by the fact that methane molecules are nonpolar and do not form hydrogen bonds with each other, whereas water molecules are polar and freely form hydrogen bonds The three-dimensional structures of these molecules are needed to help explain why water is a polar molecule and why methane is nonpolar.

Table 4 Comparing Physical Properties

Substance and formula	Water (H_2O)	Methane (CH_4)
Molecular mass	18 amu	16 amu
State at room temperature	liquid	gas
Boiling point	100°C	−162°C
Melting point	0°C	−182°C

The difference in polarity and hydrogen bonding also explains the immiscibility of alkanes and other hydrocarbons with water. If you try to dissolve alkanes, such as lubricating oils, in water, the two liquids separate almost immediately into two phases. This separation happens because the attractive forces between alkane molecules are stronger than the attractive forces between the alkane and water molecules. Therefore, alkanes are more soluble in solvents composed of nonpolar molecules like themselves than in water, a polar solvent.

Chemical properties of alkanes

The main chemical property of alkanes is their low reactivity. Recall that many chemical reactions occur when a reactant with a full electric charge, such as an ion, or with a partial charge, such as a polar molecule, is attracted to another reactant with the opposite charge. Molecules such as alkanes, in which atoms are connected by nonpolar bonds, have no charge. As a result, they have little attraction for ions or polar molecules. The low reactivity of alkanes can also be attributed to the relatively strong C–C and C–H bonds. More energy is needed to affect these bonds than is usually available in chemical collisions. With few molecular collisions having the energy to cause a reaction, these molecules will have a relatively low reactivity.

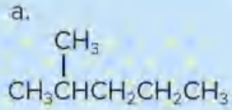
Check Your Progress

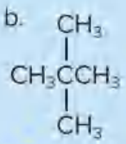
Summary

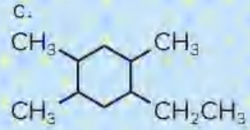
- Alkanes contain only single bonds between carbon atoms.
- Alkanes and other organic compounds are best represented by structural formulas and can be named using systematic rules determined by the International Union of Pure and Applied Chemistry (IUPAC).
- Alkanes that contain hydrocarbon rings are called cyclic alkanes.

Demonstrate Understanding

12. **Describe** the main structural characteristics of alkane molecules.
13. **Name** the following structures using IUPAC rules.

a. 

b. 

c. 

14. **Describe** the general properties of alkanes.
15. **Draw** the molecular structure for each of the following.
    a. 3,4-diethylheptane
    b. 4-isopropyl-3-methyldecane
    c. 1-ethyl-4-methylcyclohexane
    d. 1,2-dimethylcyclopropane
16. **Interpret Chemical Structures** Why is the name 3-*butylpentane* incorrect? Based on this name, write the structural formula for the compound. What is the correct IUPAC name for 3-butylpentane?

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LESSON 3
ALKENES AND ALKYNES

FOCUS QUESTION

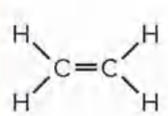
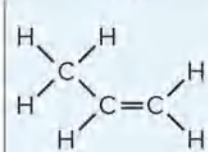
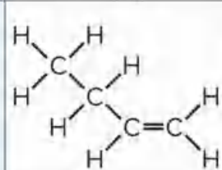
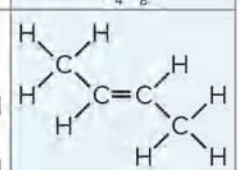
Why do some hydrocarbons form double and triple bonds?

Alkenes

Alkanes are saturated hydrocarbons because they contain only single bonds between carbon atoms. Unsaturated hydrocarbons have at least one double or triple bond between carbon atoms. Unsaturated hydrocarbons that contain one or more double covalent bonds between carbon atoms in a chain are called **alkenes.** Because an alkene must have a double bond between carbon atoms, there is no 1-carbon alkene. The simplest alkene has two carbon atoms double bonded to each other. The remaining four electrons—two from each carbon atom—are shared with four hydrogen atoms to give the molecule ethene (C_2H_4).

Alkenes with only one double bond constitute a homologous series. If you study the molecular formulas for the substances shown in **Table 5,** you will see that each has twice as many hydrogen atoms as carbon atoms. The general formula for this homologous series is C_nH_{2n}. Each alkene has two fewer hydrogen atoms than the corresponding alkane because two electrons now form the second covalent bond and are no longer available for bonding to hydrogen atoms. What are the molecular formulas for 6-carbon and 9-carbon alkenes?

Table 5 Examples of Alkenes

Name	Ethene	Propene	1-Butene	2-Butene
Molecular formula	C_2H_4	C_3H_6	C_4H_8	C_4H_8
Structural formula				
Condensed structural formula	$CH_2 = CH_2$	$CH_3CH = CH_2$	$CH_3CH_2CH = CH_2$	$CH_3CH = CHCH_3$

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Review the News

Obtain information from a current news story about alkenes and alkynes. Evaluate your source and communicate your findings to the class.

Naming alkenes

Alkenes are named in much the same way as alkanes. Their names are formed by changing the *-ane* ending of the corresponding alkane to *-ene*. An alkane with two carbons is named et*hane*, and an alkene with two carbons is named *ethene*. Likewise, a three-carbon alkene is named propene. Ethene and propene have older, more common names: *ethylene* and *propylene*, respectively.

To name alkenes with four or more carbons in the chain, it is necessary to specify the location of the double bond, as shown in **Figure 12a.** This is done by numbering the carbons in the parent chain, starting at the end of the chain that will give the first carbon in the double bond the lowest number. Then, use only that number in the name.

Note that the third structure is not "3-butene" because it is identical to the first structure, 1-butene. It is important to recognize that 1-butene and 2-butene are two different substances, each with its own properties.

Cyclic alkenes are named in much the same way as cyclic alkanes; however, carbon number 1 must be one of the carbons connected by the double bond. In **Figure 12b,** note the numbering in the compound. The name of this compound is 1,3-dimethylcyclopentene.

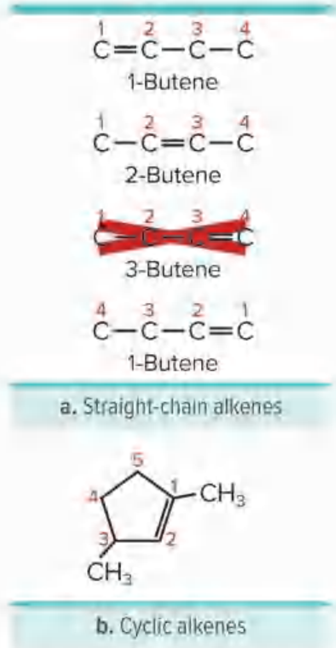


Figure 12 When naming either branched or straight alkenes, they must be numbered using IUPAC rules.

Naming branched-chain alkenes

When naming branched-chain alkenes, follow the IUPAC rules for naming branched-chain alkanes, but with two exceptions. In alkenes, the parent chain is always the longest chain that contains the double bond, whether or not it is the longest chain of carbon atoms. Second, the position of the double bond, not the branches, determines how the chain is numbered. A number specifies the location of the double bond, just as it does in straight-chain alkenes. Note that there are two 4-carbon chains in the molecule shown in **Figure 13a,** but only the one with the double bond is used as a basis for naming. This branched-chain alkene is 2-methyl-1-butene.

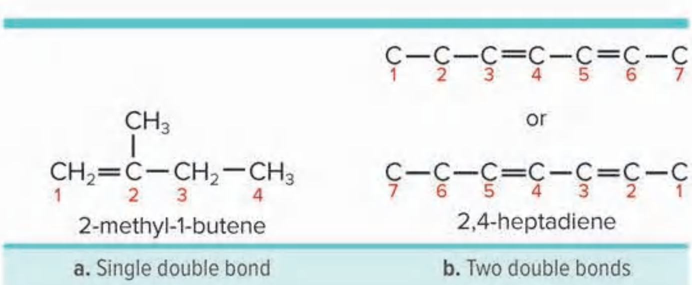
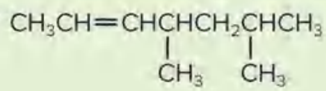


Figure 13 The positions of the double bonds in alkenes are numbered in such a way that gives the lowest set of numbers. This is true in both branched and straight-chain alkenes.

Some unsaturated hydrocarbons contain more than one double (or triple) bond. The number of double bonds in such molecules is shown by using a prefix (*di-*, *tri-*, *tetra-*, and so on) before the suffix *-ene*. The positions of the bonds are numbered in a way that gives the lowest set of numbers. Which numbering system would you use in the example in **Figure 13b**? Because the molecule has a seven-carbon chain, you would use the prefix *hepta-*. Because it has two double bonds, you would use the prefix *di-* before *-ene*, giving the name *heptadiene*. Adding the numbers 2 and 4 to designate the positions of the double bonds gives the name *2,4-heptadiene*. Note that if this chain were to be numbered from the other end of the molecule, the double bonds would be at carbons 3 and 5. However, the numbering that puts the double bonds at carbons 2 and 4 are the smaller numbers.

EXAMPLE Problem 3

NAMING BRANCHED-CHAIN ALKENES



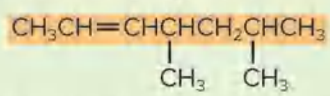
Name the alkene shown.

1 ANALYZE THE PROBLEM

You are given a branched-chain alkene that contains one double bond and two alkyl groups. Follow the IUPAC rules to name the organic compound.

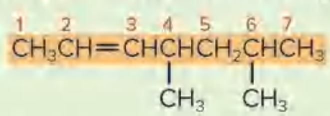
2 SOLVE FOR THE UNKNOWN

Step 1. The longest continuous-carbon chain that includes the double bond contains seven carbons. The 7-carbon alkane is heptane, but the name is changed to *heptene* because a double bond is present.



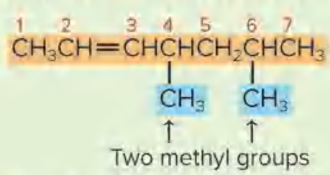
Heptene parent chain

Step 2. Number the chain to give the lowest number to the double bond.



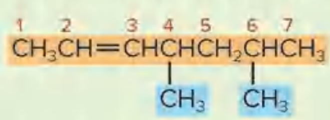
2-Heptene parent chain

Step 3. Name each substituent.



Each substituent is a methyl group.

Step 4. Determine how many of each substituent is present, and assign the correct prefix to represent that number. Then, include the position numbers to get the complete prefix.



2-Heptene parent chain

Two methyl groups at Positions 4 and 6

Prefix is 4,6-*dimethyl*

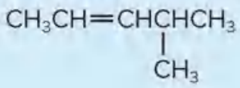
Step 5. The names of substituents do not have to be alphabetized because they are the same. Apply the complete prefix to the name of the parent alkene chain. Use commas between numbers, and hyphens between numbers and words. Write the name 4,6-*dimethyl-2-heptene*.

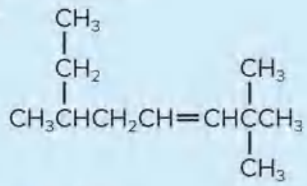
3 EVALUATE THE ANSWER

The longest carbon chain includes the double bond, and the position of the double bond has the lowest possible number. Correct prefixes and alkyl group names designate the branches.

PRACTICE Problems ADDITIONAL PRACTICE

17. Use the IUPAC rules to name the following structures.

a. 

b. 

18. CHALLENGE Draw the structure of 1,3-pentadiene.

Figure 14 The use of ethene to ripen produce allows growers to harvest fruits and vegetables before they ripen. Explain why this is a benefit to growers.

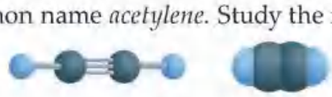
Properties and uses of alkenes

Like alkanes, alkenes are nonpolar and therefore have low solubility in water as well as relatively low melting and boiling points. However, alkenes are more reactive than alkanes because the second covalent bond increases the electron density between two carbon atoms, providing a good site for chemical reactivity. Reactants that attract electrons can pull the electrons away from the double bond.

Several alkenes occur naturally in living organisms. For example, ethene is a hormone produced naturally by plants. It causes fruit to ripen and plays a part in causing leaves to fall from deciduous trees in preparation for winter. The fruits shown in **Figure 14** and other produce sold in grocery stores ripen artificially when they are exposed to ethene. Ethene is also the starting material for the synthesis of the plastic polyethylene, which is used to manufacture many products, including plastic bags, rope, and milk jugs. Other alkenes are responsible for the scents of lemons, limes, and pine trees.

Alkynes

Unsaturated hydrocarbons that contain one or more triple bonds between carbon atoms in a chain are called **alkynes.** Triple bonds involve the sharing of three pairs of electrons. The simplest and most commonly used alkyne is ethyne (C_2H_2), which is widely known by its common name *acetylene.* Study the models of ethyne in **Figure 15.**

$H—C\equiv C—H$ 

Models of ethyne (acetylene)

Figure 15 These three molecular models represent ethyne.

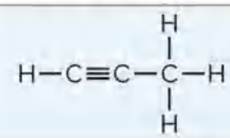
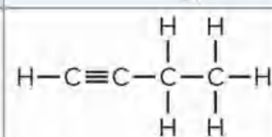
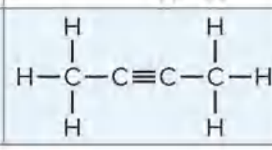
Naming alkynes

Straight-chain alkynes and branched-chain alkynes are named in the same way as alkenes. The only difference is that the name of the parent chain ends in *-yne* rather than *-ene*. Study the examples in **Table 6.** Alkynes with one triple covalent bond form a homologous series with the general formula C_nH_{2n-2}.

Get It?

Infer by looking at the bonds in ethyne why it is highly reactive with oxygen.

Table 6 Examples of Alkynes

Name	Molecular Formula	Structural Formula	Condensed Structural Formula
Ethyne	C_2H_2	$H-C\equiv C-H$	$CH\equiv CH$
Propyne	C_3H_4		$CH\equiv CCH_3$
1-Butyne	C_4H_6		$CH\equiv CCH_2CH_3$
2-Butyne	C_4H_6		$CH_3C\equiv CCH_3$

Properties and Uses of Alkynes

Alkynes have physical and chemical properties similar to those of alkenes. Alkynes undergo many of the reactions alkenes undergo. However, alkynes are generally more reactive than alkenes because the triple bonds of alkynes have even greater electron density than the double bonds of alkenes. This cluster of electrons is effective at inducing dipoles in nearby molecules, causing them to become unevenly charged and thus reactive.

Ethyne—known commonly as acetylene—is a by-product of oil refining and is also made in large quantities by the reaction of calcium carbide (CaC_2) with water. When supplied with enough oxygen, ethyne burns with an intensely hot flame that can reach temperatures as high as 3000°C. Acetylene torches are commonly used in metal cutting and welding as shown in **Figure 16** on the next page. Because the triple bond makes alkynes reactive, simple alkynes like ethyne are used as starting materials in the manufacture of plastics and other organic chemicals used in industry.

STEM CAREER Connection

Welders, Cutters, Solderers, and Brazers

If you enjoy working with your hands and working in a variety of locations and conditions, a career in welding may be for you. Welders, cutters, solderers, and brazers work with acetylene torches to join or cut metals. They also fill holes or seams between metals. Some welders couple this occupation with their love for scuba diving to work underwater as a welder.

Figure 16 Ethyne, or acetylene, reacts with oxygen in the chemical reaction $2C_2H_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O$, which produces enough heat to cut through metals.

The reaction of calcium carbide with water was historically used in the mining industry to generate lamps. The first carbide mining lamp was patented in August of 1900 by Frederick Baldwin. The drip rate of water onto the solid calcium carbide would control how much of the gas was generated, thus controlling the amount of light the lamp would generate.

Check Your Progress

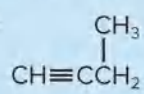
Summary

- Alkenes and alkynes are hydrocarbons that contain at least one double or triple bond, respectively.
- Alkenes and alkynes are nonpolar compounds with greater reactivity than alkanes but with other properties similar to those of alkanes.

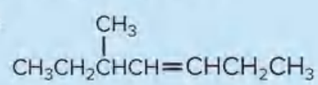
Demonstrate Understanding

19. **Describe** how the molecular structures of alkenes and alkynes differ from the structure of alkanes.
20. **Identify** how the chemical properties of alkenes and alkynes differ from those of alkanes.
21. **Name** the structures shown using IUPAC rules.

a.



b.



22. **Draw** the molecular structure of 4-methyl-1, 3-pentadiene and 2,3-dimethyl-2-butene.
23. **Infer** how the boiling and freezing points of alkynes compare with those of alkanes with the same number of carbon atoms. Explain your reasoning, then research data to see if it supports your idea.
24. **Predict** What geometric arrangements would you expect from the bonds surrounding the carbon atom in alkanes, alkenes, and alkynes? (*Hint: VSEPR theory can be used to predict the shape.*)

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LESSON 4

HYDROCARBON ISOMERS

FOCUS QUESTION

In how many different ways can a set number of carbon and hydrogen atoms be arranged?

Structural Isomers

Examine **Figure 17** to determine how they are similar and how the three alkanes are different. All three have 5 carbon atoms and 12 hydrogen atoms, so they have the molecular formula C_5H_{12}. However, these models represent three different arrangements of atoms and three different compounds–pentane, 2-methylbutane, and 2,2-dimethylpropane. These three compounds are isomers. **Isomers** are compounds that have the same molecular formula but different molecular structures. Note that cyclopentane and pentane are not isomers because cyclopentane's molecular formula is C_5H_{10}.

There are two main classes of isomers. **Figure 17** shows examples of structural isomers. **Structural isomers** have the same chemical formula, but their atoms are bonded in different arrangements. Structural isomers have different chemical and physical properties despite having the same formula. This observation supports one of the main principles of chemistry: The structure of a substance determines its properties. How does the trend in boiling points of C_5H_{12} isomers relate to their molecular structures?

As the number of carbons in a hydrocarbon increases, the number of possible structural isomers increases. For example, there are nine alkanes with the molecular formula C_7H_{16}. There are more than 300,000 structural isomers with the formula $C_{20}H_{42}$.

Pentane
bp = 36°C

2-Methylbutane
bp = 28°C

2,2-Dimethylpropane
bp = 9°C

Figure 17 These compounds with the same molecular formula, C_5H_{12}, are structural isomers.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Laboratory: Isomerism

Develop an investigation to compare and contrast the shapes of several organic molecules.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

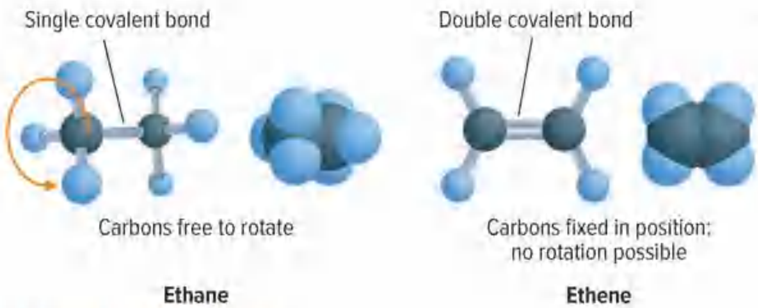

Figure 18 The single-bonded carbons in ethane are free to rotate around the bond. The double-bonded carbons in ethane resist being rotated.

Stereoisomers

The second class of isomers involves a more subtle difference in bonding. **Stereoisomers** are isomers in which all atoms are bonded in the same order but are arranged differently in space. There are two types of stereoisomers. One type occurs in alkenes, which contain double bonds. Two carbon atoms with a single bond between them can rotate freely in relationship to each other. However, when a second covalent bond is present, the carbons can no longer rotate; they are locked in place, as shown in **Figure 18.**

Get It?
Explain *How do you think this difference in ability to rotate would affect atoms or groups of atoms bonded to single-bonded and double-bonded atoms?*

Compare the two possible structures of 2-butene shown in **Figure 19.** The arrangement in which the two methyl groups are on the same side of the molecule is indicated by the prefix *cis-*. The arrangement in which the two methyl groups are on opposite sides of the molecule is indicated by the prefix *trans-*. These terms derive from Latin: *cis* means *on the same side*, and *trans* means *across from*.

Isomers resulting from different arrangements of groups around a double bond are called **geometric isomers.** Note how the difference in geometry affects the isomers' physical properties, such as melting point and boiling point. Geometric isomers differ in some chemical properties as well. If the compound is biologically active, such as a drug, the *cis-* and *trans-* isomers usually have very different effects.

Get It?
Explain how structural and geometric isomers differ.

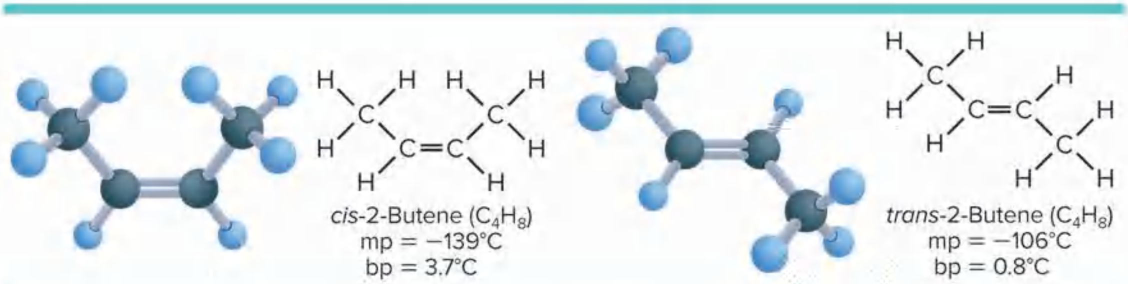

Figure 19 These isomers of 2-butene differ in the arrangement in the space of the two methyl groups at the ends. The double-bonded carbon atoms cannot rotate with respect to each other, so the methyl groups are fixed in one of these two arrangements.

Figure 20 The reflection of your right hand looks the same as your left hand. However, you cannot place your hands palms down with one on top of the other and have matching parts lie on top of each other.

Chirality

BIOLOGY Connection In 1848, the young French chemist Louis Pasteur (1822–1895) reported his discovery that crystals of the organic compound tartaric acid existed in two shapes that were mirror images of each other. Because a person's hands are like mirror images, as shown in **Figure 20,** the crystals were called the right-handed and left-handed forms. The two forms of tartaric acid had the same chemical properties, melting point, density, and solubility in water, but only the left-handed form was produced by fermentation to make wine. In addition, bacteria were able to multiply only when they were fed the left-handed form as a nutrient.

The two crystalline forms of tartaric acid exist in the two arrangements shown in **Figure 21.** Today, these two forms are called d-tartaric acid and l-tartaric acid. The letters d and l stand for the Latin prefixes *dextro-*, which means *to the right*, and *levo-*, which means *to the left*. The property in which a molecule exists in a right- and l eft-handed form is called **chirality.** Many of the substances found in living organisms, such as the amino acids that make up proteins, have this chirality. In general, living organisms make use of only one chiral form of a substance because only this form fits the active site of an enzyme.

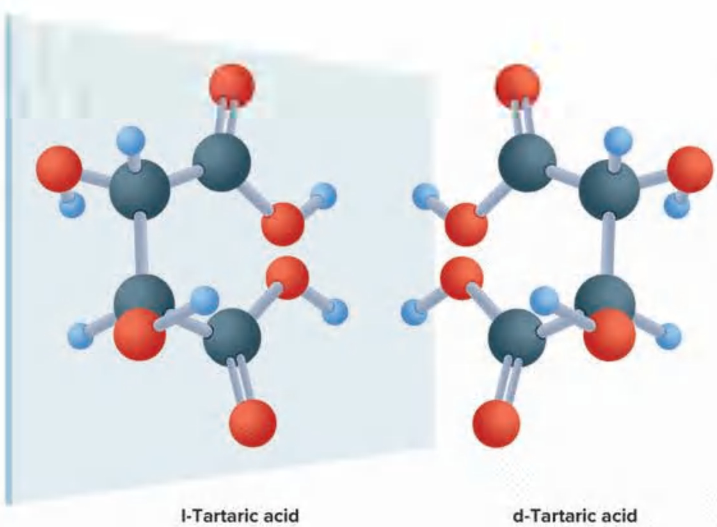

Figure 21 These models represent the two forms of tartaric acid that Pasteur studied. If the model of right-handed tartaric acid (d-tartaric acid) is reflected in a mirror, its image is a model of the left-handed tartaric acid (l-tartaric acid).

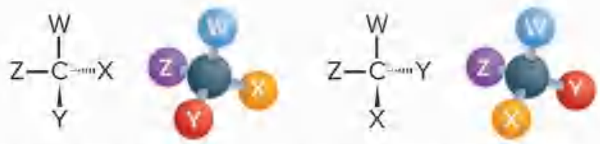

Figure 22 These molecules represent two different molecules. Groups X and Y have switched places.

Optical Isomers

In the 1860s, chemists realized that chirality occurs whenever a compound contains an asymmetric carbon. An **asymmetric carbon** is a carbon atom that has four different atoms or groups of atoms attached to it. The four groups can always be arranged in two different ways. Suppose that groups W, X, Y, and Z are attached to the same carbon atom in the two arrangements shown in **Figure 22.** Note that the structures differ in that groups X and Y have been exchanged. You cannot rotate the two arrangements in any way that will make them identical to each other.

Now suppose that you build models of these two structures. Is there any way you could turn one structure so that it looks the same as the other? (Whether letters appear forward or backward does not matter.) You would discover that there is no way to accomplish the task without removing X and Y from the carbon atom and switching their positions. Therefore, the molecules are different even though they look very much alike.

Isomers that result from different arrangements of four different groups around the same carbon atom represent another class of stereoisomers called optical isomers. **Optical isomers** have the same physical and chemical properties, except in chemical reactions where chirality is important, such as enzyme-catalyzed reactions in biological systems. Human cells, for example, incorporate only l-amino acids into proteins. Only the l-form of ascorbic acid is active as vitamin C. The chirality of a drug molecule can also be important. For example, only one isomer of some drugs is effective and the other isomer can be harmful.

Optical rotation

Mirror-image isomers are called optical isomers because they affect light passing through them. Normally, the light waves in a beam from the Sun or a lightbulb move in all possible planes. However, light can be filtered or reflected in such a way that the resulting waves all lie in the same plane. This type of light is called polarized light.

When polarized light passes through a solution containing an optical isomer, the plane of polarization is rotated to the right (clockwise, when looking toward the light source) by a d-isomer or to the left (counterclockwise) by an l-isomer, producing an effect called **optical rotation.** This effect is shown in **Figure 23** on the next page.

One optical isomer that you might have used is l-menthol. This natural isomer has a strong, minty flavor, and a cooling odor and taste. The mirror-image isomer, d-menthol, does not have the same cooling effect as l-menthol, which further verifies that optical isomers of the same chemical formula are truly different molecules structurally.

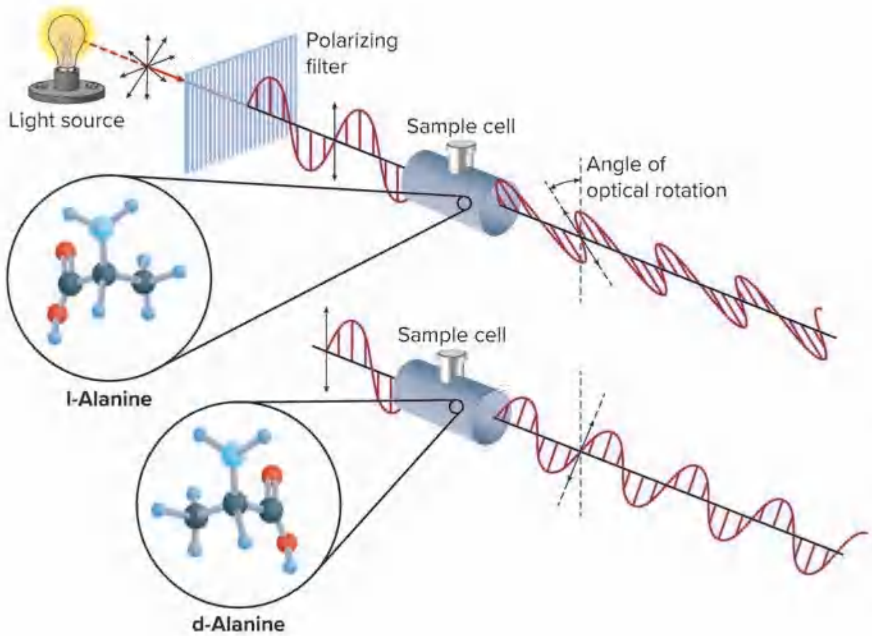

Figure 23 Polarized light can be produced by passing ordinary light through a filter that transmits light waves that lie only in one plane. Here, the filtered light waves are in a vertical plane before they pass through the sample cells. The two isomers rotate the light in different directions.

Check Your Progress

Summary

- Isomers are two or more compounds with the same molecular formula but different molecular structures.
- Structural isomers differ in the order in which atoms are bonded to each other.
- Stereoisomers have all atoms bonded in the same order but arranged differently in space.

Demonstrate Understanding

25. **Draw** all of the structural isomers possible for the alkane with the molecular formula C_6H_{14}. Show only the carbon chains.
26. **Explain** the difference between structural isomers and stereoisomers.
27. **Draw** the structures of *cis*-3-hexene and *trans*-3-hexene.
28. **Infer** why living organisms can make use of one only chiral form of a substance.
29. **Evaluate** A certain reaction yields 80% *trans*-2-pentene and 20% *cis*-2-pentene. Draw the structures of these two geometric isomers, and develop a hypothesis to explain why the isomers form in the proportions cited.
30. **Formulate Models** Starting with a single carbon atom, draw two different optical isomers by attaching the following atoms or groups to the carbon: $-H$, $-CH_3$, $-CH_2CH_3$, and $-CH_2CH_2CH_3$.

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LESSON 5
AROMATIC HYDROCARBONS

FOCUS QUESTION

What do mothballs, wintergreen, and aspirin have in common?

The Structure of Benzene

Natural dyes, like those found in the fabrics in **Figure 24,** and essential oils for perfumes contain six-carbon ring structures. Compounds with these structures have been used for centuries. By the middle of the nineteenth century, chemists had a basic understanding of the structures of hydrocarbons with single, double, and triple covalent bonds. However, certain hydrocarbon ring structures remained a mystery.

The simplest example of this class of hydrocarbon is benzene, which the English physicist Michael Faraday (1791–1867) first isolated in 1825 from the gases given off when either whale oil or coal was heated. Although chemists had determined that benzene's molecular formula was C_6H_6, it was hard for them to determine what sort of hydrocarbon structure would give such a formula. After all, the formula of the saturated hydrocarbon with six carbon atoms, hexane, was C_6H_{14}. Because the benzene molecule had so few hydrogen atoms, chemists reasoned that it must be unsaturated; that is, it must have several double or triple bonds, or a combination of both. They proposed many different structures, including this one suggested in 1860.

$$CH_2{=}C{=}CH{-}CH{=}C{=}CH_2$$

Figure 24 Dyes used to produce brightly colored fabrics have been used for centuries.

Get It?
Explain *What do many natural dyes and essential oils for perfumes have in common?*

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COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

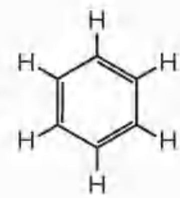
Identify Crosscutting Concepts
Create a table of the crosscutting concepts and fill in examples you find as you read.

Review the News
Obtain information from a current news story about aromatic hydrocarbons. Evaluate your source and communicate your findings to the class.

Although this structure has a molecular formula of C_6H_6, such a hydrocarbon would be unstable and extremely reactive because of its many double bonds. However, benzene was fairly unreactive, and it did not react in the ways that alkenes and alkynes usually react. For that reason, chemists reasoned that structures such as the linear structure proposed in 1860 must be incorrect.

Kekulé's dream

In 1865, the German chemist Friedrich August Kekulé (1829–1896) proposed a different kind of structure for benzene—a hexagon of carbon atoms with alternating single and double bonds. How does the molecular formula of this structure compare with that of benzene?



Kekulé claimed that benzene's structure came to him in a dream. He said that he had dreamed of the Ouroboros, an ancient Egyptian emblem of a snake devouring its own tail, and that had made him think of a ring-shaped structure. The flat, hexagonal structure he proposed explained some of the properties of benzene, but it did not explain the lack of reactivity.

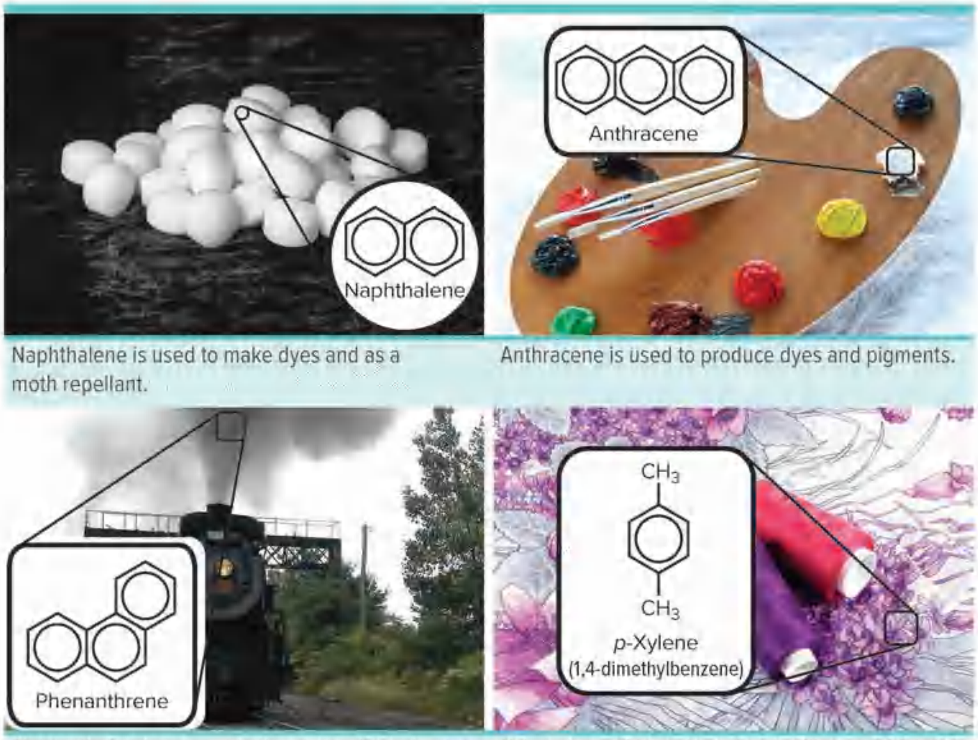
A modern model of benzene

Since the time of Kekulé's proposal, research has confirmed that benzene's molecular structure is indeed hexagonal. However, benzene's unreactivity could not be explained until the 1930s, when Linus Pauling proposed the theory of hybrid orbitals. When applied to benzene, this theory predicts that the pairs of electrons that form the second bond of each of benzene's double bonds are not localized between only two specific carbon atoms as they are in alkenes. Instead, the electron pairs are delocalized, which means they are shared among all six carbons in the ring. **Figure 25** shows that this delocalization makes the benzene molecule chemically stable because electrons shared by six carbon nuclei are harder to pull away than electrons held by only two nuclei. The six hydrogen atoms are usually not shown, but it is important to remember that they are there. In this representation, the circle in the middle of the hexagon symbolizes the cloud formed by the three pairs of electrons.

Figure 25 Benzene's bonding electrons spread evenly in a double-donut shape around the ring instead of remaining near individual atoms.

Aromatic Compounds

Organic compounds that contain benzene rings as part of their structures are called **aromatic compounds.** The term *aromatic* was originally used because many of the benzene-related compounds known in the nineteenth century were found in pleasant-smelling oils that came from spices, fruits, and other plant parts. Hydrocarbons such as the alkanes, alkenes, and alkynes are called **aliphatic compounds** to distinguish them from aromatic compounds. The term *aliphatic* comes from the Greek word for *fat*, which is *aleiphatos*. Early chemists obtained aliphatic compounds by heating animal fats.



Naphthalene is used to make dyes and as a moth repellant.

Anthracene is used to produce dyes and pigments.

Phenanthrene is present in the atmosphere due to the incomplete combustion of hydrocarbons.

Xylene is used to make polyester fibers and fabrics.

Figure 26 Aromatic hydrocarbons are found in the environment due to the incomplete combustion of hydrocarbons and are used to make a variety of products.

Structures of some aromatic compounds are shown in **Figure 26.** Note that naphthalene has a structure that looks like two benzene rings arranged side by side. Naphthalene is an example of a fused-ring system, in which an organic compound has two or more cyclic structures with a common side. As in benzene, electrons are shared by the carbon atoms that make up the ring systems.

Naming substituted aromatic compounds

Like other hydrocarbons, aromatic compounds can have many different groups attached to the carbon atoms of the ring structure. For example, methylbenzene, also known as toluene, consists of a methyl group attached to a benzene ring in place of one hydrogen atom.

SCIENCE USAGE v. COMMON USAGE

aromatic

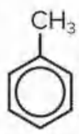
Science usage: an organic compound with increased chemical stability due to the delocalization of electrons

Benzene is a compound classified as an aromatic.

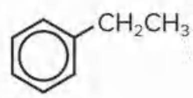
Common usage: having strong odor or smell

The perfume was very aromatic.

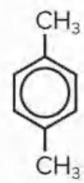
Substituted benzene compounds are named in the same way as cyclic alkanes. For example, ethylbenzene has a 2-carbon ethyl group attached, and 1,4-dimethylbenzene, also known as *para*-xylene, has two methyl groups attached at positions 1 and 4.



Methylbenzene (toluene)

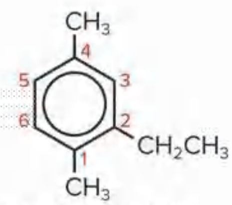


Ethylbenzene



1,4-Dimethylbenzene (*para*-xylene)

Just as with substituted cycloalkanes, substituted benzene rings are numbered in a way that gives the lowest-possible numbers for the substituents, as shown in **Figure 27.** Numbering the ring as shown gives the numbers 1, 2, and 4 for the substituent positions. Because *ethyl* comes before *methyl* in the alphabet, it is written first in the name: 2-ethyl-1,4-dimethylbenzene.



2-Ethyl-1,4-dimethylbenzene

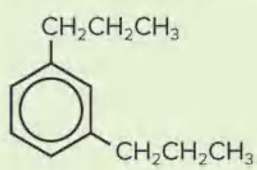
Figure 27 Substituted benzene rings are named in the same way as cyclic alkanes.

Get It?

Explain what the circle means inside the six-membered ring structure in **Figure 27.**

EXAMPLE Problem 4

NAMING AROMATIC COMPOUNDS Name the aromatic compound shown.

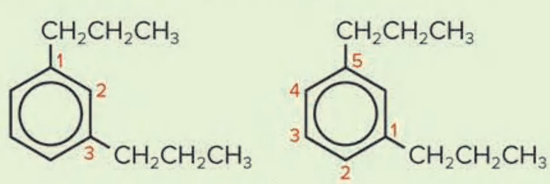


1 ANALYZE THE PROBLEM

You are given an aromatic compound. Follow the rules to name the aromatic compound.

2 SOLVE FOR THE UNKNOWN

Step 1. Number the carbon atoms to give the lowest numbers possible.



EXAMPLE Problem 4 (continued)

As you can see, the numbers 1 and 3 are lower than the numbers 1 and 5. So the numbers used to name the hydrocarbon should be 1 and 3.

Step 2. Determine the name of the substituents. If the same substituent appears more than once, add the prefix to show the number of groups present.

Step 3. Put the name together. Alphabetize the substituent names, and use commas between numbers and hyphens between numbers and words. Write the name as 1,3-*dipropylbenzene*.

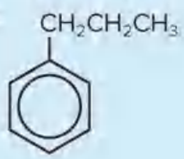
3 EVALUATE THE ANSWER

The benzene ring is numbered to give the branches the lowest possible set of numbers. The names of the substituent groups are correctly identified.

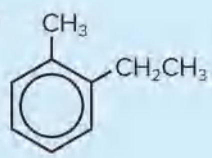
PRACTICE Problems ADDITIONAL PRACTICE

31. Name the following structures.

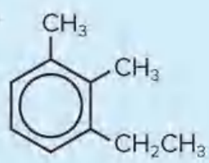
a.



b.



c.



32. CHALLENGE Draw the structure of 1,4-dimethylbenzene.

Carcinogens

Many aromatic compounds, particularly benzene, toluene, and xylene, were once commonly used as industrial and laboratory solvents. However, tests have shown that the use of such compounds should be limited because they can affect the health of people who are exposed to them regularly. Health risks linked to aromatic compounds include respiratory ailments, liver problems, and damage to the nervous system. Beyond these hazards, some aromatic compounds are carcinogens, which are substances that can cause cancer.

Some of these compounds are still used today. For example, toluene is still used in some paints, paint thinners, silicone sealers, and nail polish removers. It is also an important ingredient in the manufacturing of explosives for the mining industry. TNT, or trinitrotoluene requires toluene in its production. Benzene is an additive in gasoline and is used in the production of plastics, synthetic fibers, detergents and resins.

With these chemicals still in use today, extra care must be taken to avoid unnecessary health risks. Proper ventillation in areas where these chemicals are used and respirators worn by those handling the chemicals are just two of the many precautions that can be taken.

As scientists research and develop new organic compounds, proper safety precautions must always be taken until the properties of the new compound are fully understood.

Figure 28 Benzopyrene is a cancer-causing chemical that is found in soot, cigarette smoke, and car exhaust.

The first known carcinogen was an aromatic substance discovered around the turn of the twentieth century in chimney soot. Chimney sweeps in Great Britain were known to have abnormally high rates of cancer. Scientists discovered that the cause of the cancer was the aromatic compound benzopyrene, shown in **Figure 28.** This compound is a by-product of the burning of complex mixtures of organic substances, such as wood and coal. Some aromatic compounds found in gasoline are also known to be carcinogenic.

Check Your Progress

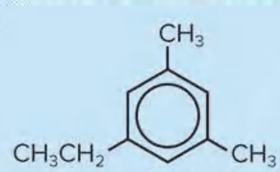
Summary

- Aromatic hydrocarbons contain benzene rings as part of their molecular structures.
- The electrons in aromatic hydrocarbons are shared evenly over the entire benzene ring.

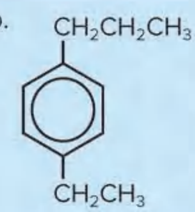
Demonstrate Understanding

33. **Explain** benzene's structure and how it makes the molecule unusually stable.
34. **Explain** how aromatic hydrocarbons differ from aliphatic hydrocarbons.
35. **Describe** the properties of benzene that made chemists think it was not an alkene with several double bonds.
36. **Name** the following structures.

a.



b.



37. **Explain** why the connection between benzopyrene and cancer was significant.

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SCIENTIFIC BREAKTHROUGHS

Like Oil and Water

Ocean oil spills are devastating to marine plants and animals, and they can foul shorelines for thousands of miles. They are also notoriously tricky to clean up. In the past, chemicals have been used in clean-up efforts. But like the oil itself, chemicals can harm marine organisms. In response, scientists have developed more environmentally friendly and efficient ways to remove crude oil from water.

This vessel was part of the clean up of the Deepwater Horizon oil spill in the Gulf of Mexico in 2010.

Mesh nets and nanoparticles

In 2015, scientists in Ohio looked to nature to develop a stainless steel mesh net coated with different substances that can separate oil from water. Silica nanoparticles form the first incredibly thin, bumpy layer of the coating. Scientists developed the nanoparticles after studying the bumpy, water-repelling leaves of lotus plants. They wanted to mimic this effect—but they wanted to repel oil, not water.

To accomplish this task, scientists used a surfactant, which reduces the surface tension of liquids. They mixed it with a polymer to bind together the layers and applied it to the net on top of the silica nanoparticles. The result? Water passes through the net, while oil remains on top of the net. People can then lift the net and take the oil out of the water.

Supergelators

In 2016, scientists at a government institute in Singapore developed a product they call "supergelators." This substance is made of organic molecules that, when sprayed on an oil spill, stack themselves up to form slender nanofibers. The nanofibers come together to form thicker nanofibers, which in turn form a gel-like net that traps oil. People can then use a sieve to scoop the oil out of the water.

The Singapore researchers say that supergelators are inexpensive, nontoxic, fast-acting, and easy to use. Once the oil is removed from the water, the process of fractional distillation can reclaim the oil for other uses.

SEP DCI CCC

CONSTRUCT AN ARGUMENT FROM EVIDENCE

Work with a partner to find more information on these two methods of cleaning up an oil spill. Use print or online sources. Together, decide which method you think is better, and write a short paper that supports your argument with evidence from your sources.

STUDY GUIDE

GO ONLINE What are the characteristics and reactions of hydrocarbons?

Lesson 1 INTRODUCTION TO HYDROCARBONS

- Organic compounds contain the element carbon, which is able to form straight chains and branched chains.
- Hydrocarbons are organic substances composed of carbon and hydrogen.
- The major sources of hydrocarbons are petroleum and natural gas.
- Petroleum can be separated into components by the process of fractional distillation.

- organic compound
- hydrocarbon
- saturated hydrocarbon
- unsaturated hydrocarbon
- fractional distillation
- cracking

Lesson 2 ALKANES

- Alkanes contain only single bonds between carbon atoms.
- Alkanes and other organic compounds are best represented by structural formulas and can be named using systematic rules determined by the International Union of Pure and Applied Chemistry (IUPAC).
- Alkanes that contain hydrocarbon rings are called cyclic alkanes.

- alkane
- homologous series
- parent chain
- substituent group
- cyclic hydrocarbon
- cycloalkane

Lesson 3 ALKENES AND ALKYNES

- Alkenes and alkynes are hydrocarbons that contain at least one double or triple bond, respectively.
- Alkenes and alkynes are nonpolar compounds with greater reactivity than alkanes but with other properties similar to those of alkanes.

- alkene
- alkyne

Lesson 4 HYDROCARBON ISOMERS

- Isomers are two or more compounds with the same molecular formula but different molecular structures.
- Structural isomers differ in the order in which atoms are bonded to each other.
- Stereoisomers have all atoms bonded in the same order but arranged differently in space.

- isomer
- structural isomer
- stereoisomer
- geometric isomer
- chirality
- asymmetric carbon
- optical isomer
- optical rotation

Lesson 5 AROMATIC HYDROCARBONS

- Aromatic hydrocarbons contain benzene rings as part of their molecular structures.
- The electrons in aromatic hydrocarbons are shared evenly over the entire benzene ring.

- aromatic compound
- aliphatic compound

THREE-DIMENSIONAL THINKING
Module Wrap-Up

REVISIT THE PHENOMENON

What is fueling this natural fire?

CER Claim, Evidence, Reasoning

Explain your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

Based on Real Data*

SEP Data Analysis Lab

What are the rates of oxidation of dichloroethene isomers?

Pseudomonas butanovora is a bacterium that was tested as an agent to rid groundwater of dichloroethene (DCE) contaminants. Mixtures containing various reducing agents and butane monooxygenase in *Pseudomonas butanovora* oxidized isomers of DCE.

Data and Observations The table shows the rate of oxidation of each compound in butane-grown *P. butanovora.* Table values in parentheses represent the increase (*n*-fold) above the buffer rate.

Rates of Oxidation

	Initial Rate of Oxidation (n mol min^{-1} mg protein^{-1})	
Reducing Agent	**1,2-cis DCE**	**1,2-trans DCE**
Buffer	0.9 (1.0)	1.6 (1.0)
Butyrate	6.8 (7.6)	2.0 (1.3)
Propionate	5.9 (6.6)	0.4 (0.3)
Acetate	8.5 (9.4)	3.8 (2.8)
Formate	1.4 (1.6)	1.2 (0.7)
Lactate	11 (12.2)	4.5 (2.8)

*Data obtained from: Doughty, D.M. et al. 2005. Effects of dichloroethene isomers on the induction and activity of butane monooxygenase in the alkane-oxidizing Bacterium "*Pseudomonas butanovora*." *Applied Environmental Microbiology.* October: 6054–6059.

CER Analyze and Interpret Data

1. **Claim, Evidence, Reasoning** Which reducing agent was most useful in oxidizing each isomer? Explain.
2. **Claim, Evidence, Reasoning** Which isomer oxidized the slowest? Explain.

SUBSTITUTED HYDROCARBONS AND THEIR REACTIONS

SUBSTITUTED HYDROCARBONS AND THEIR REACTIONS

ENCOUNTER THE PHENOMENON

Where do natural and synthetic dyes get their colors?

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

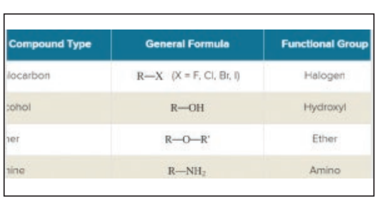
CER Claim, Evidence, Reasoning

Make Your Claim Use your CER chart to make a claim about where natural and synthetic dyes get their color.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

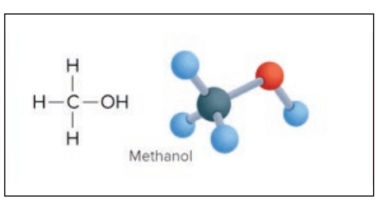
Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.



Compound Type	General Formula	Functional Group
locarbon	R—X (X = F, Cl, Br, I)	Halogen
cohol	R—OH	Hydroxyl
her	R—O—R'	Ether
nine	$R—NH_2$	Amino

LESSON 1: Explore & Explain: Functional Groups



LESSON 2: Explore & Explain: Alcohols, Ethers, and Amines

LESSON 1

ALKYL HALIDES AND ARYL HALIDES

FOCUS QUESTION

How does a hydrocarbon's properties change if you replace one of the hydrogens with a chlorine or fluorine atom?

Functional Groups

You read previously that in hydrocarbons, carbon atoms are linked only to other carbon atoms or hydrogen atoms. But carbon atoms can also form strong covalent bonds with other elements, the most common of which are oxygen, nitrogen, fluorine, chlorine, bromine, iodine, sulfur, and phosphorus.

Atoms of these elements occur in organic substances as parts of functional groups. In an organic molecule, a **functional group** is an atom or group of atoms that always reacts in a certain way. The addition of a functional group to a hydrocarbon structure always produces a substance with physical and chemical properties that differ from those of the parent hydrocarbon. All the items—natural and synthetic—in **Figure 1** contain functional groups that give them their individual characteristics, such as smell.

Figure 1 All of these items contain at least one of the functional groups that you will study in this module. For example, the fruit and flowers have sweet-smelling aromas that are due to ester molecules.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Virtual Investigation: Functional Groups

Use models to compare and contrast the functional groups of organic compounds in relation to the outcome of simple chemical reactions.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Table 1 Organic Compounds and Their Functional Groups

Compound Type	General Formula	Functional Group
Halocarbon	R—X (X = F, Cl, Br, I)	Halogen
Alcohol	R—OH	Hydroxyl
Ether	R—O—R'	Ether
Amine	$R-NH_2$	Amino
Aldehyde	$*-\overset{O}{\overset{\Vert}{C}}-H$	Carbonyl
Ketone	$R-\overset{O}{\overset{\Vert}{C}}-R'$	Carbonyl
Carboxylic acid	$*-\overset{O}{\overset{\Vert}{C}}-OH$	Carboxyl
Ester	$*-\overset{O}{\overset{\Vert}{C}}-O-R$	Ester
Amide	$*-\overset{O}{\overset{\Vert}{C}}-\overset{*}{\overset{\vert}{N}}-*$	Amide

You can see the names of a few types of organic compounds that contain several important functional groups in **Table 1.** The symbols R and R' in the general formulas represent carbon chains or rings bonded to the functional group. An * represents a hydrogen atom, carbon chain, or carbon ring.

Keep in mind that double and triple bonds between two carbon atoms are considered functional groups even though only carbon and hydrogen atoms are involved. Investigating new structures requires a detailed examination of different materials, the structures of different components, and the connections of components to reveal their function. By learning the properties associated with a given functional group, you can predict the properties of organic compounds for which you know the structure, even if you have never studied them.

Organic Compounds Containing Halogens

The most simple functional groups can be thought of as substituent groups attached to a hydrocarbon. Recall that a substituent group is a side branch attached to a parent chain. The elements in group 17 of the periodic table—fluorine, chlorine, bromine, and iodine—are the halogens. Any organic compound that contains a halogen substituent is called a **halocarbon.** If you replace any of the hydrogen atoms in an alkane with a halogen atom, you form an alkyl halide.

Get It?
Identify the types of organic compounds that contain a carbonyl group.

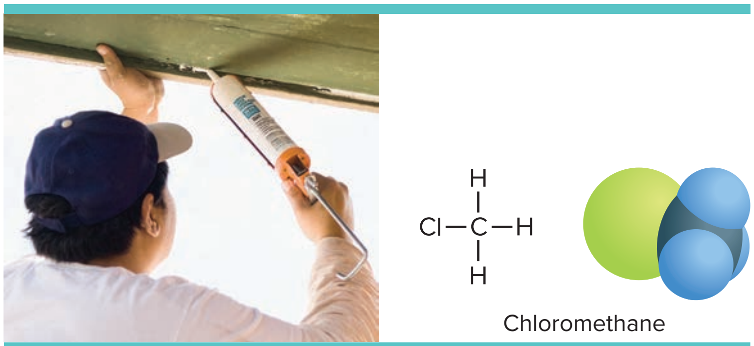


Figure 2 Chloromethane is an alkyl halide that is used in the manufacturing process for silicone products, such as window and door sealants.

An **alkyl halide** is an organic compound containing a halogen atom covalently bonded to an aliphatic carbon atom. The first four halogens—fluorine, chlorine, bromine, and iodine—are found in many organic compounds. For example, chloromethane is the alkyl halide formed when a chlorine atom replaces one of methane's four hydrogen atoms, as shown in **Figure 2.**

An **aryl halide** is an organic compound containing a halogen atom bonded to a benzene ring or other aromatic group. The structural formula for an aryl halide is created by first drawing the aromatic structure and then replacing its hydrogen atoms with the halogen atoms specified. Remember that a benzene ring is represented as a hexagon (for the six carbon atoms that make up the ring) with a circle inside it (for the cloud formed by the three delocalized pairs of electrons). Replacing one of the hydrogens with chlorine results in chlorobenzene, as shown in **Figure 3a.**

Naming halocarbons

Organic molecules containing functional groups are given IUPAC names based on their main-chain alkane structures. For the alkyl halides, a prefix indicates which halogen is present. The prefixes are formed by changing the *-ine* at the end of each halogen name to *-o*. Thus, the prefix for fluorine is *fluoro-*, chlorine is *chloro-*, bromine is *bromo-*, and iodine is *iodo-*. The chain is numbered to give the lowest number at the first point of difference, as shown in **Figure 3b.** Notice that the prefix *di-* in 1,2-difluoropropane indicates that the molecule has two hydrogen atoms replaced by fluorine atoms.

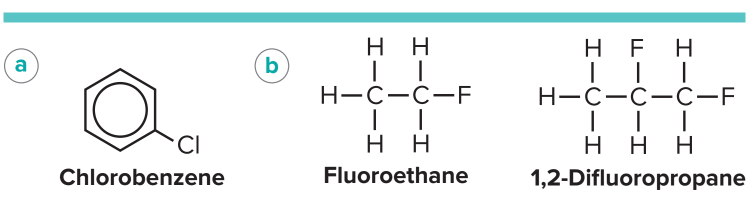


Figure 3 These organic molecules are halides, as indicated by the halogen atoms represented in these structures. The name of an organic halide includes a prefix based on the halogen's name.

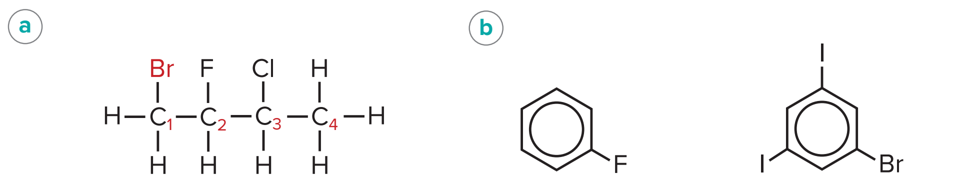


Figure 4 Organic molecules containing functional groups are named based on their main-chain structure using IUPAC conventions.

If more than one kind of halogen atom is present in the same molecule, the atoms are listed alphabetically in the name. Note how the alkyl halide in **Figure 4a** is named.

Similarly, the benzene ring in an aryl halide is numbered to give each substituent the lowest position number possible. If numbering is identical in two directions, give the lowest position number to the substituent that will be first in the name, as shown in **Figure 4b.**

EARTH SCIENCE Connection Alkyl halides are widely used as refrigerants. Until the late 1980s, alkyl halides called chlorofluorocarbons (CFCs) were widely used in refrigerators and air-conditioning systems. Because of their role in damaging the ozone layer, CFCs have been replaced by HFCs (hydrofluorocarbons). Molecules of hydrofluorocarbons contain only hydrogen atoms and fluorine atoms bonded to carbon atoms. One of the more common HFCs is 1,1,1,2-tetrafluoroethane, also called R134a.

Get It?

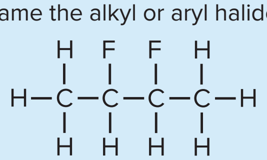
Infer why the lowest possible position number is used to name an aryl halide instead of using a randomly chosen position number.

PRACTICE Problems

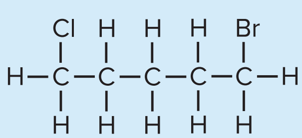
ADDITIONAL PRACTICE

Name the alkyl or aryl halide whose structure is shown.

1.



2.



3.

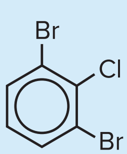


Table 2 A Comparison of Alkyl Halides and Their Parent Alkanes

Structure	Name	Boiling Point (°C)	Density (g/mL) in Liquid State
CH_4	methane	–162	0.423 at –162°C (boiling point)
CH_3Cl	chloromethane	–24	0.911 at 25°C (under pressure)
$CH_3CH_2CH_2CH_2CH_3$	pentane	36	0.626
$CH_3CH_2CH_2CH_2CH_2F$	1-fluoropentane	62.8	0.791
$CH_3CH_2CH_2CH_2CH_2Cl$	1-chloropentane	108 Increases	0.882 Increases
$CH_3CH_2CH_2CH_2CH_2Br$	1-bromopentane	130	1.218
$CH_3CH_2CH_2CH_2CH_2I$	1-iodopentane	155	1.516

Properties and uses of halocarbons

It is easiest to talk about properties of organic compounds containing functional groups by comparing those compounds with alkanes, whose properties you have already studied. **Table 2** lists some of the physical properties of certain alkanes and alkyl halides.

Compare the boiling points and densities of methane and chloromethane in **Table 2.** Next, compare the boiling points and densities of pentane and 1-chloropentane. Note that each alkyl chloride has a higher boiling point and a higher density than the alkane with the same number of carbon atoms.

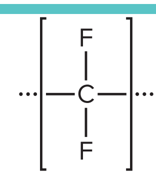
Now compare the boiling points and densities of the halogen-substituted pentanes. Note that the boiling points and densities increase as the halogen changes from fluorine to chlorine, bromine, and iodine. This trend occurs primarily because the halogens from fluorine to iodine have increasing numbers of electrons that lie farther from the halogen nucleus. These electrons shift position easily and, as a result, the halogen-substituted hydrocarbons have an increasing tendency to form temporary dipoles. Because the dipoles attract each other, the energy needed to separate the molecules also increases. Thus, the boiling points of halogen-substituted alkanes increase as the size of the halogen atom increases.

Get It?

Explain the relationship between the number of electrons in the halogen and the boiling point.

Organic halides are seldom found in nature, although human thyroid hormones are organic iodides. Halogen atoms bonded to carbon atoms are more reactive than the hydrogen atoms they replace. For this reason, alkyl halides are often used as starting materials in the chemical industry. Alkyl halides are also used as solvents and cleaning agents because they readily dissolve nonpolar molecules, such as greases.

Figure 5 shows an application of polytetrafluoroethene (PTFE), a plastic made from gaseous tetrafluoroethylene. A **plastic** is a polymer that can be heated and molded while relatively soft. Another plastic commonly called *vinyl* is polyvinyl chloride (PVC). It can be manufactured soft or hard, as thin sheets, or molded into objects.



PTFE

Get It?

Explain why alkyl halides are often used in the chemical industry as starting materials instead of alkanes.

Figure 5 Polytetrafluoroethene (PTFE) is made up of hundreds of units. PTFE provides a nonstick surface for many kitchen items, including bakeware.

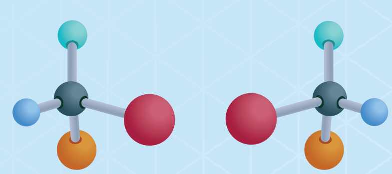
Check Your Progress

Summary

- The substitution of functional groups for hydrogen in hydrocarbons creates a wide variety of organic compounds.
- An alkyl halide is an organic compound that has one or more halogen atoms bonded to a carbon atom in an aliphatic compound.

Demonstrate Understanding

4. **Compare and contrast** alkyl halides and aryl halides.
5. **Draw** structures for the following molecules.
   a. 2-chlorobutane
   b. 1,3-difluorohexane
   c. 1,1,1-trichloroethane
   d. 1-bromo-4-chlorobenzene
6. **Define** *functional group* and name the group present in each of the following structures. Name the type of organic compound each substance represents.
   a. $CH_3CH_2CH_2OH$
   b. CH_3CH_2F
   c. $CH_3CH_2NH_2$
   d. $CH_3\overset{\overset{\large O}{\|}}{C}-OH$
7. **Evaluate** How would you expect the boiling points of propane and 1-chloropropane to compare? Explain your answer.
8. **Interpret Scientific Illustrations** Examine the pair of substituted hydrocarbons shown, and decide whether it represents a pair of optical isomers. Explain your answer.



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LESSON 2

ALCOHOLS, ETHERS, AND AMINES

FOCUS QUESTION

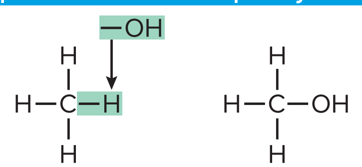
How does adding -OH or -NH_3 change the properties of a hydrocarbon?

Alcohols

Many organic compounds contain oxygen atoms bonded to carbon atoms. Because an oxygen atom has six valence electrons, it commonly forms two covalent bonds to gain a stable octet. An oxygen atom can form a double bond with a carbon atom, replacing two hydrogen atoms, or it can form one single bond with a carbon atom and another single bond with another atom, such as hydrogen. An oxygen-hydrogen group covalently bonded to a carbon atom is called a **hydroxyl group** (–OH). An organic compound in which a hydroxyl group replaces a hydrogen atom of a hydrocarbon is called an **alcohol.** As shown in **Table 3,** the general formula for an alcohol is ROH. **Table 3** also illustrates the relationship of the simplest alkane, methane, to the simplest alcohol, methanol.

Ethanol and carbon dioxide are produced by yeasts when they ferment sugars, such as those in grapes and bread dough. Ethanol is found in alcoholic beverages and medicinal products. Because it is an effective antiseptic, ethanol can be used to swab skin before an injection is given. It is also a gasoline additive and an important starting material for the synthesis of more complex organic compounds.

Table 3 Alcohols

General Formula	Simple Alcohol and Simple Hydrocarbon
ROH R represents carbon chains or rings bonded to the functional group	 Methane (CH_4) Methanol (CH_3OH) **Alkane** **Alcohol**

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

ChemLAB: Observe Properties of Alcohols

Obtain, evaluate, and communicate information to model the relative strength of intermolecular forces of alcohols to describe and predict chemical reactions.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

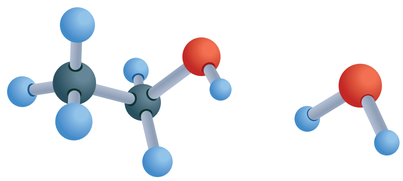


Figure 6 The covalent bonds from oxygen have approximately the same bonding angle in ethanol and water.

Figure 6 shows a model of an ethanol molecule and a model of a water molecule. As you compare the models, notice that the covalent bonds from the oxygen in ethanol are at roughly the same angle as the bonds around the oxygen in the water molecule. Therefore, the hydroxyl groups of alcohol molecules are moderately polar, as with water, and are able to form hydrogen bonds with the hydroxyl groups of other alcohol molecules. Due to this hydrogen bonding, alcohols have much higher boiling points than hydrocarbons of similar shape and size.

Also, because of polarity and hydrogen bonding, ethanol is completely miscible with water. In fact, once they are mixed, it is difficult to separate water and ethanol completely. Distillation is used to remove ethanol from water, but even after that process is complete, about 5% water remains in the ethanol-water mixture.

On the shelves of drugstores, you can find bottles of ethanol labeled *denatured alcohol*. **Denatured alcohol** is ethanol to which small amounts of noxious materials, such as aviation gasoline or other organic solvents, have been added. Ethanol is denatured in order to make it unfit to drink.

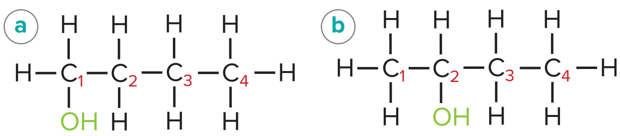
Because of their polar hydroxyl groups, alcohols make good solvents for other polar organic substances. For example, methanol, the smallest alcohol, is a common industrial solvent found in some paint strippers, and 2-butanol is found in some stains and varnishes.

Get It?

Explain the difference in boiling points between alcohols and hydrocarbons of similar shape and size.

ACADEMIC VOCABULARY

bond
to connect, bind, or join
An oxygen atom bonds to two carbon atoms in an ether.



1-Butanol 2-Butanol

Figure 7 The names of alcohols are based on alkane names.

Note that the names of alcohols are based on alkane names, like the names of alkyl halides. For example, CH_4 is methane, and CH_3OH is methanol; CH_3CH_3 is ethane, and CH_3CH_2OH is ethanol. When naming a simple alcohol based on an alkane carbon chain, the IUPAC rules call for naming the parent carbon chain or ring first and then changing the *-e* at the end of the name to *-ol* to indicate the presence of a hydroxyl group. In alcohols of three or more carbon atoms, the hydroxyl group can be at two or more positions. To indicate the position, a number is added, as shown in **Figure 7.**

Get It?

Explain why *4-butanol* and *3-butanol* are not the correct names for the compounds in **Figure 7.**

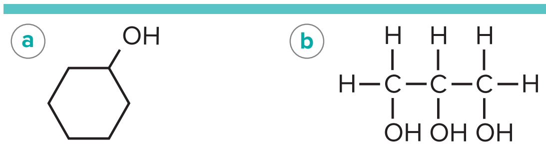
Now look at **Figure 8a.** The compound's ring structure contains six carbons with only single bonds, so you know that the parent hydrocarbon is cyclohexane. Because an –OH group is bonded to a carbon, it is an alcohol and the name will end in *-ol*. No number is necessary because all carbons in the ring are equivalent. This compound is called cyclohexanol. It is a poisonous compound used as a solvent for certain plastics and in the manufacture of insecticides.

A carbon chain can also have more than one hydroxyl group. To name these compounds, prefixes such as *di-*, *tri-*, and *tetra-* are used before the *-ol* to indicate the number of hydroxyl groups present. The full alkane name, including *-ane*, is used before the prefix.

Figure 8b shows the molecule 1,2,3-propanetriol, commonly called glycerol. It is an alcohol containing more than one hydroxyl group. Glycerol is often used as an antifreeze and as an airplane deicing fluid.

Get It?

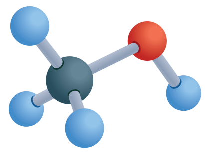
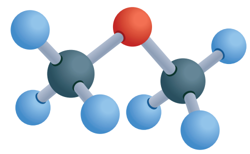
Explain why numbers are not used to name the compound shown in **Figure 8a.**

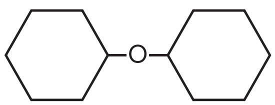


Cyclohexanol 1,2,3-Propanetriol (glycerol)

Figure 8 Alcohols can include one or more hydroxyl groups.

Table 4 Ethers

General Formula	Methanol and Methyl Ether	
ROR´ where R and R´ represent carbon chains or rings bonded to functional groups	 Methanol bp = 65°C	 Methyl ether bp = −25°C

Examples of Ethers	
 Cyclohexyl ether	$CH_3CH_2CH_2—O—CH_2CH_2CH_3$ Propyl ether
$CH_3CH_2—O—CH_2CH_2CH_2CH_3$ Butyl ethyl ether	$CH_3CH_2—O—CH_3$ Ethyl methyl ether

Ethers

Ethers are another group of organic compounds in which oxygen is bonded to carbon. An **ether** is an organic compound containing an oxygen atom bonded to two carbon atoms. Ethers have the general formula ROR′, as shown in **Table 4.** The simplest ether is one in which oxygen is bonded to two methyl groups. Note the similarity between methanol and methyl ether shown in **Table 4.**

The term *ether* was first used in chemistry as a name for ethyl ether, the volatile, highly flammable substance that was commonly used as an anesthetic in surgery from 1842 until the twentieth century. As time passed, the term *ether* was applied to other organic substances having two hydrocarbon chains attached to the same oxygen atom.

Because ethers have no hydrogen atoms bonded to the oxygen atom, their molecules cannot form hydrogen bonds with each other. Therefore, ethers are generally more volatile and have much lower boiling points than alcohols of similar size and mass.

Also because of the lack of hydrogen atoms bonded to the oxygen atom, ethers are much less soluble in water than alcohols. Ethers have no hydrogen to donate to a hydrogen bond with a water molecule. However, the oxygen atom of the ether can act as a hydrogen bond receptor for the hydrogen atoms of water molecules.

Get It?

Infer why ethyl ether is undesirable as an anesthetic.

When naming ethers that have two identical alkyl chains bonded to oxygen, first name the alkyl group and then add the word *ether*. **Table 4** shows the structures and names of two of these symmetrical ethers, propyl ether and cyclohexyl ether. If the two alkyl groups are different, the groups are listed in alphabetical order and then followed by the word *ether*. **Table 4** contains two examples of these asymmetrical ethers, butyl ethyl ether and ethyl methyl ether.

Amines

Amines contain nitrogen atoms bonded to carbon atoms in aliphatic chains or aromatic rings and have the general formula RNH_2, as shown in **Table 5.**

Chemists consider amines to be derivatives of ammonia (NH_3). Amines are considered primary, secondary, or tertiary amines depending on whether one, two, or three of the hydrogens in ammonia have been replaced by organic groups.

When naming amines, the $–NH_2$ (amino) group is indicated by the suffix *-amine*. When necessary, the position of the amino group is designated by a number, as shown in the examples in **Table 5.** When only one amino group is present, the final *-e* of the root hydrocarbon is dropped, as in 1-butanamine. If more than one amino group is present, the prefixes *di-*, *tri-*, *tetra-* and so on are used to indicate the number of groups.

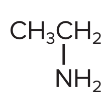
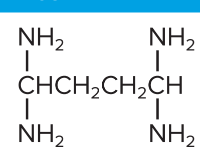
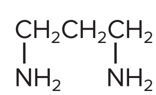
The amine aniline is used in the production of dyes with deep shades of color. The common name *aniline* is derived from the plant from which it was historically obtained. Cyclohexylamine and ethylamine are important in the manufacture of pesticides, plastics, pharmaceuticals, and rubber that is used to make tires.

All volatile amines have odors that humans find offensive, and amines are responsible for many of the odors characteristic of dead, decaying organisms. Two amines found in decaying human remains are putrescine and cadaverine. Specially trained dogs are used to locate human remains using these distinctive odors. Sniffer dogs are often used after catastrophic events and in forensic investigations.

Get It?

Infer how an understanding of amines might be useful in developing dyes like the ones in the module opener.

Table 5 **Amines**

General Formula				
RNH_2 where R represents a carbon chain or ring bonded to the functional group				
Examples of Amines				
 Cyclohexylamine	 Ethylamine	 Aniline	 1,1,4,4-Butanetetraamine	 1,3-Propanediamine

Substitution Reactions

From where does the immense variety of organic compounds come? Amazingly enough, the ultimate source of nearly all synthetic organic compounds is petroleum. The oil-field workers shown in **Figure 9** are drilling for petroleum, which is a fossil fuel that consists almost entirely of hydrocarbons, especially alkanes. How can alkanes be converted into compounds as different as alkyl halides, alcohols, and amines?

Figure 9 These oil-field workers are drilling for petroleum. A single oil well can extract more than 100 barrels per day.

Explain *the relationship between petroleum and synthetic organic compounds.*

One way is to introduce a functional group through substitution, as shown in **Table 6.** A **substitution reaction** is one in which one atom or a group of atoms in a molecule is replaced by another atom or group of atoms. With alkanes, hydrogen atoms can be replaced by atoms of halogens, typically chlorine or bromine, in a process called **halogenation.** One example of a halogenation reaction, shown in **Table 6,** is the substitution of a chlorine atom for one of ethane's hydrogen atoms. **Figure 10** on the next page shows another halogenated hydrocarbon commonly called halothane (2-bromo-2-chloro-1,1,1-trifluoroethane), which was first used as a general anesthetic in the 1950s.

Equations for organic reactions are sometimes shown in generic form. **Table 6** shows the generic form of a substitution reaction. In this reaction, *X* can be fluorine, chlorine, or bromine, but not iodine. Iodine does not react well with alkanes.

Get It?

Draw the molecular structure of halothane.

Table 6 Substitution Reactions

Generic Substitution Reaction $R{-}CH_3 + X_2 \rightarrow R{-}CH_2X + HX$ where X is fluorine, chlorine, or bromine	**Example of General Substitution Reaction (Halogenation)** $C_2H_6 + Cl_2 \rightarrow C_2H_5Cl + HCl$ Ethane Chloroethane
General Alkyl Halide-Alcohol Reaction $R{-}X + OH^- \rightarrow R{-}OH + X^-$ Alkyl halide Alcohol	**Example of an Alkyl Halide-Alcohol Reaction** $CH_3CH_2Cl + OH^- \rightarrow CH_3CH_2OH + Cl^-$ Chloroethane Ethanol
General Alkyl Halide-Ammonia Reaction $R{-}X + NH_3 \rightarrow R{-}NH_2 + HX$ Alkyl halide Amine	**Example of an Alkyl Halide-Ammonia Reaction** $CH_3(CH_2)_6CH_2Br + NH_3 \rightarrow CH_3(CH_2)_6CH_2NH_2 + HBr$ 1-Bromooctane 1-Octanamine

Further substitution

Once an alkane has been halogenated, the resulting alkyl halide can undergo other types of substitution reactions in which the halogen atom is replaced by another atom or group of atoms. For example, reacting an alkyl halide with a basic solution results in the replacement of the halogen atom by an –OH group, forming an alcohol. An example of an alkyl halide-alcohol reaction is shown in **Table 6.** The generic form of the alkyl halide-alcohol reaction is also shown in **Table 6.**

Reacting an alkyl halide with ammonia (NH_3) replaces the halogen atom with an amino group (–NH_2), forming an alkyl amine, also shown in **Table 6.** The alkyl amine is one of the products produced in this reaction. Some of the newly formed amines continue to react, resulting in a mixture of amines.

Figure 10 Halothane was introduced into medicine in the 1950s as a general anesthetic for patients undergoing surgery.

Check Your Progress

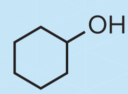
Summary

- Alcohols, ethers, and amines are formed when specific functional groups substitute for hydrogen in hydrocarbons.
- Because they readily form hydrogen bonds, alcohols have higher boiling points and higher water solubilities than other organic compounds.

Demonstrate Understanding

9. **Identify** two elements that are commonly found in functional groups.
10. **Identify** the functional group present in each of the following structures. Name the substance represented by each structure.

    a. NH_2 attached to the central carbon of CH_3CHCH_3

    b. 

    c. $CH_3{-}O{-}CH_2CH_2CH_3$
11. **Draw** the structure for each molecule.

    a. 1-propanol
    c. propyl ether
    b. 1,3-cyclopentanediol
    d. 1,2-propanediamine
12. **Discuss** the properties of alcohols, ethers, and amines, and give one use of each.
13. **Analyze** Based on their structures, which compound is likely more water-soluble? Explain your reasoning.

    $CH_3{-}O{-}CH_3$ $\qquad$ CH_3CH_2 with OH on the CH_2

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LESSON 3

CARBONYL COMPOUNDS

FOCUS QUESTION

How do hydroxyl groups and carbonyl groups functionally compare?

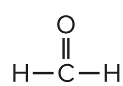
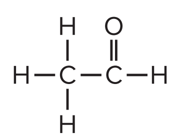
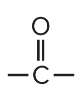
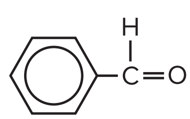
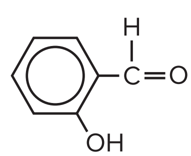
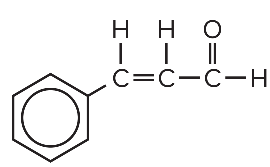
Organic Compounds Containing the Carbonyl Group

The arrangement in which an oxygen atom is double-bonded to a carbon atom is called a **carbonyl group.** This group is the functional group in organic compounds known as aldehydes and ketones.

Aldehydes

An **aldehyde** is an organic compound in which a carbonyl group located at the end of a carbon chain is bonded to a carbon atom on one side and a hydrogen atom on the other. Aldehydes have the general formula *CHO, where * represents an alkyl group or a hydrogen atom, as shown in **Table 7.**

Table 7 Aldehydes

General Formula	Examples of Aldehydes		
*CHO *represents an alkyl group or a hydrogen atom	 Methanal (formaldehyde)		 Ethanal (acetaldehyde)
 Carbonyl group	 Benzaldehyde	 Salicylaldehyde	 Cinnamaldehyde

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

ChemLAB: Make an Ester

Construct and explanation for the function of the compound created by a simple chemical reaction.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Aldehydes are formally named by changing the final *-e* of the name of the alkane with the same number of carbon atoms to the suffix *-al*. Thus, the formal name of the compound methanal, shown in **Table 7,** is based on the one-carbon alkane methane.

Because the carbonyl group in an aldehyde always occurs at the end of a carbon chain, no numbers are used in the name unless branches or additional functional groups are present. Methanal is also commonly called formaldehyde. Ethanal has the common name *acetaldehyde.* Scientists often use the common names of organic compounds because they are familiar to chemists.

An aldehyde molecule contains a polar, reactive structure. However, like ethers, aldehyde molecules cannot form hydrogen bonds among themselves because the molecules have no hydrogen atoms bonded to an oxygen atom. Therefore, aldehydes have lower boiling points than alcohols with the same number of carbon atoms. Water molecules can form hydrogen bonds with the oxygen atom of aldehydes, so aldehydes are more soluble in water than alkanes but not as soluble as alcohols or amines.

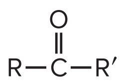
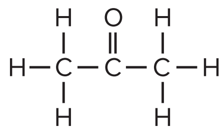
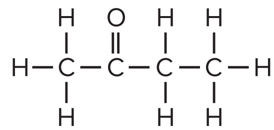
Formaldehyde has been used for preservation for many years, as shown in **Figure 11.** Industrially, large quantities of formaldehyde are reacted with urea to manufacture a type of grease-resistant, hard plastic used to make buttons, appliance and automotive parts, and electrical outlets, as well as the glue that holds the layers of plywood together.

The other aldehydes shown in **Table 7** occur naturally. Benzaldehyde and salicylaldehyde are two components that give almonds their natural flavor. Cinnamon is a spice that comes from the bark of a tropical tree. Its distinctive aroma and flavor are produced largely by cinnamaldehyde.

Get It?
Identify two uses for aldehydes.

Figure 11 A water solution of formaldehyde was used in the past to preserve biological specimens. However, formaldehyde's use has been restricted in recent years because studies indicate it might cause cancer.

Table 8 Ketones

General Formula	Examples of Ketones	
 where R and R´ represent carbon chains or rings bonded to functional groups	 2-Propanone (acetone)	 2-Butanone (methyl ethyl ketone)

Ketone

A carbonyl group can also be located within a carbon chain rather than at the end. A **ketone** is an organic compound in which the carbon of the carbonyl group is bonded to two other carbon atoms. Ketones have the general formula shown in **Table 8.** The carbon atoms on either side of the carbonyl group are bonded to other atoms. The simplest ketone, commonly known as acetone, has only hydrogen atoms bonded to the side carbons, as shown in **Table 8.**

Get It?

Identify How many hydrogen atoms are bonded to the carbon atom in the carbonyl group of a ketone?

Ketones are formally named by changing the *-e* at the end of the alkane name to *-one*, and including a number before the name to indicate the position of the ketone group. In the previous example, the alkane name propane is changed to propan*one*. The carbonyl group can be located only in the center, but the prefix 2- is usually added to the name for clarity, as shown in **Table 8.**

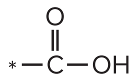
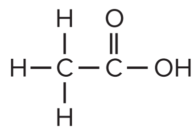
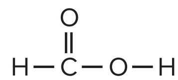
Get It?

Explain why the name of a ketone will not use the prefix *1-* to indicate the location of the carbonyl group.

Ketones and aldehydes share many chemical and physical properties because their structures are similar. Ketones are polar molecules and are less reactive than aldehydes. For this reason, ketones are popular solvents for other moderately polar substances, including waxes, plastics, paints, lacquers, varnishes, and glues.

Like aldehydes, ketone molecules cannot form hydrogen bonds with each other but can form hydrogen bonds with water molecules. Therefore, ketones are somewhat soluble in water. Acetone is completely miscible with water.

Table 9 Carboxylic Acids

General Formula	Examples of Carboxylic Acids	
 where * represents a hydrogen atom, carbon chain, or ring bonded to the functional group	 Ethanoic acid (acetic acid)	 Methanoic acid (formic acid)

Carboxylic Acids

A **carboxylic acid** is an organic compound that has a carboxyl group. A **carboxyl group** consists of a carbonyl group bonded to a hydroxyl group. Thus, carboxylic acids have the general formula shown in **Table 9.** One diagram shown in **Table 9** is the structure of a familiar carboxylic acid—acetic acid, the acid found in vinegar. Although many carboxylic acids have common names, the formal name is formed by changing the *-ane* of the parent alkane to *-anoic acid*. Thus, the formal name of acetic acid is ethanoic acid.

A carboxyl group is usually represented in condensed form by writing –COOH. For example, ethanoic acid can be written as CH_3COOH. The simplest carboxylic acid consists of a carboxyl group bonded to a single hydrogen atom, HCOOH, shown in **Table 9.** Its formal name is methanoic acid, but it is more commonly known as formic acid. Some insects produce formic acid as a defense mechanism, as shown in **Figure 12.**

Get It?

Explain Stinging ants use formic acid, or methanoic acid, as a defense mechanism. How is the name *methanoic acid* derived?

Carboxylic acids are polar and reactive. Those that dissolve in water ionize weakly to produce hydronium ions, the anion of the acid in equilibrium with water, and the unionized acid. The ionization of ethanoic acid is an example.

$$CH_3COOH(aq) + H_2O(l) \rightleftharpoons CH_3COO^-(aq) + H_3O^+(aq)$$

Ethanoic acid (acetic acid) Ethanoate ion (acetate ion)

Carboxylic acids can ionize in water solution because the two oxygen atoms are highly electronegative and attract electrons away from the hydrogen atom in the –OH group. As a result, the hydrogen proton can transfer to another atom that has a pair of electrons not involved in bonding, such as the oxygen atom of a water molecule. Because they ionize in water, soluble carboxylic acids turn blue litmus paper red and have a sour taste.

Figure 12 Stinging ants defend themselves with a venom that contains formic acid.

Identify *another name for formic acid.*

Some important carboxylic acids, such as oxalic acid and adipic acid, have two or more carboxyl groups. An acid with two carboxyl groups is called a dicarboxylic acid. Others have additional functional groups such as hydroxyl groups, as in the lactic acid found in yogurt. Typically, these acids are more soluble in water and often more acidic than acids with only a carboxyl group.

Get It?

Evaluate Using the information presented, explain why carboxylic acids are classified as acids.

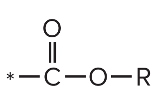
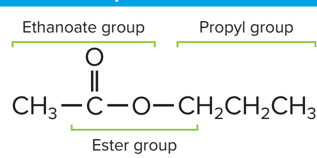
Organic Compounds Derived from Carboxylic Acids

Several classes of organic compounds have structures in which the hydrogen or the hydroxyl group of a carboxylic acid is replaced by a different atom or group of atoms. The two most common classes are esters and amides.

Esters

An **ester** is any organic compound with a carboxyl group in which the hydrogen of the hydroxyl group has been replaced by an alkyl group, producing the arrangement shown in **Table 10.** The name of an ester is formed by writing the name of the alkyl group followed by the name of the acid with the *-ic acid* ending replaced by *-ate*, as illustrated by the example shown in **Table 10.** Note how the name *propyl* results from the structural formula. The name shown in parentheses is based on the name *acetic acid,* the common name for ethanoic acid.

Table 10 Esters

General Formula	Examples of an Ester
 Ester group	 Propyl ethanoate (propyl acetate)

SCIENCE USAGE v. COMMON USAGE

class

Science usage: a group, set, or kind that share common traits

Esters are a class of organic molecules.

Common usage: a group of students that meet at regular intervals to study the same subject

Students meet for chemistry class during fourth period.

CCC CROSSCUTTING CONCEPTS

Structure and Function **Figure 13** on the next page illustrates two natural occurrences of esters. In a chart, list the functional groups you have learned in this module. For each, provide an example of a naturally occurring molecule that contains the functional group. Gather evidence that reveals each molecule's properties and function.

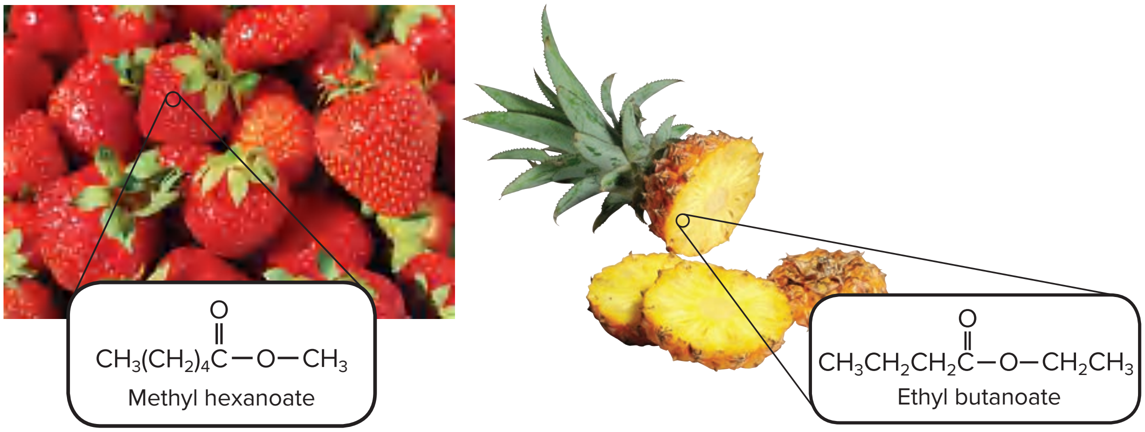


Figure 13 Esters are responsible for the flavors and aromas of many fruits. The aroma of strawberries is due in part to methyl hexanoate. Ethyl butanoate contributes to the aroma of pineapple. Most natural aromas and flavors are mixtures of esters, aldehydes, and alcohols.

Esters are polar molecules and many are volatile and sweet-smelling. Many kinds of esters are found in the natural fragrances and flavors of flowers and fruits, as shown in **Figure 13.** Natural flavors, such as apple or banana, result from mixtures of many different organic molecules, including esters, but some of these flavors can be imitated by a single ester structure. Consequently, esters are manufactured for use as flavors in many foods and beverages and as fragrances in candles, perfumes, and other scented items.

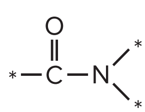
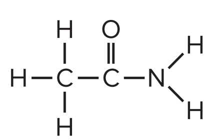
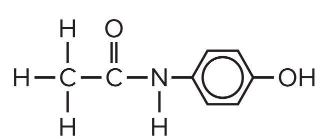
Amides

A second class of compounds derived from carboxylic acids is amides. An **amide** is an organic compound in which the –OH group of a carboxylic acid is replaced by a nitrogen atom bonded to other atoms. The general structure of an amide is shown in **Table 11.** Amides are named by writing the name of the alkane with the same number of carbon atoms, and then replacing the final *-e* with *-amide*. Thus, the amide shown in **Table 11** is called ethanamide, but it can also be named acetamide from its common name, acetic acid.

Get It?

Describe how an amide differs from a carboxylic acid.

Table 11 **Amides**

General Formula	Examples of Amides	
 Amide group	 Ethanamide (acetamide)	 Acetaminophen

The amide functional group is found repeated many times in natural proteins and some synthetic materials. For example, you might have used a nonaspirin pain reliever containing acetaminophen. In the acetaminophen structure shown in **Table 11,** notice that the amide group connects an alkyl group and an aromatic group.

Get It?

Identify Examine the structural formulas of ethanamide and acetaminophen in **Table 11.** What components do the molecules share that allow each compound to be classified as an amide?

One important amide is carbamide (NH_2CONH_2), or urea, as it is commonly known. Urea is an end product in the metabolic breakdown of proteins in mammals. It is found in the blood, bile, milk, and perspiration of mammals. When proteins are broken down, amino groups (NH_2) are removed from the amino acids. The amino groups are then converted to ammonia (NH_3) molecules that are toxic to the body. The toxic ammonia is converted to nontoxic urea in the liver. The urea is filtered out of the blood in the kidneys and passed from the body in urine.

Because of the high nitrogen content of urea and because it is easily converted to ammonia in the soil, urea is a common commercial fertilizer. Urea is also used as a protein supplement for ruminant animals, such as cattle and sheep. These animals use urea to produce proteins in their bodies.

Get It?

Identify an amide that is found in the human body.

Condensation Reactions

Many laboratory syntheses and industrial processes involve the reaction of two organic reactants to form a larger organic product, such as the aspirin shown in **Figure 14.** This type of reaction is known as a condensation reaction.

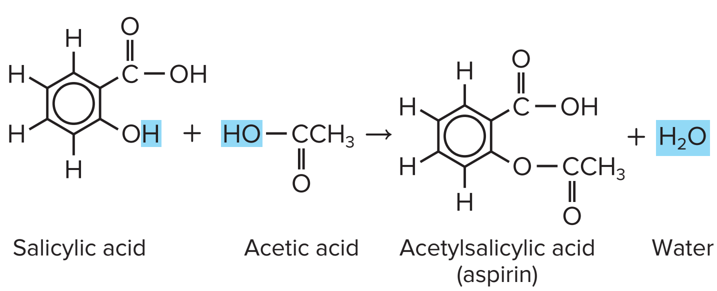


Figure 14 To synthesize aspirin, two organic molecules are combined in a condensation reaction to form a larger molecule.

In a **condensation reaction,** two smaller organic molecules combine to form a more complex molecule, accompanied by the loss of a small molecule such as water. Typically, the molecule lost is formed from one particle from each of the reactant molecules. In essence, a condensation reaction is an elimination reaction in which a bond is formed between two atoms not previously bonded to each other.

Get It?

Identify the atoms lost from each particle in the condensation reaction for the synthesis of aspirin shown in **Figure 14.** Then, identify the small molecule lost in the reaction and the new functional group that forms.

The most common condensation reactions involve the combining of carboxylic acids with other organic molecules. A common way to synthesize an ester is by a condensation reaction between a carboxylic acid and an alcohol. Such a reaction can be represented by the following general equation.

$$RCOOH + R'OH \rightarrow RCOOR' + H_2O$$

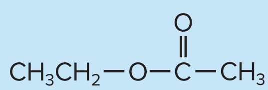
Check Your Progress

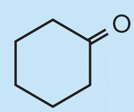
Summary

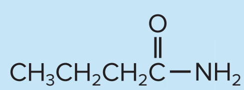
- Carbonyl compounds are organic compounds that contain the C=O group.
- Five important classes of organic compounds containing carbonyl compounds are aldehydes, ketones, carboxylic acids, esters, and amides.

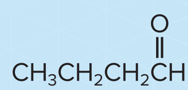
Demonstrate Understanding

14. **Classify** each of the carbonyl compounds as one of the types of organic substances you have studied in this lesson.

a. 

c. 

b. 

d. 

15. **Describe** the products of a condensation reaction between a carboxylic acid and an alcohol.
16. **Determine** The general formula for alkanes is C_nH_{2n+2}. Derive a general formula to represent an aldehyde, a ketone, and a carboxylic acid.
17. **Infer** why water-soluble organic compounds with carboxyl groups exhibit acidic properties in solutions, whereas similar compounds with aldehyde structures do not exhibit these properties.

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LESSON 4

OTHER REACTIONS OF ORGANIC COMPOUNDS

FOCUS QUESTION

What are some reactions typical of organic compounds?

Classifying Reactions of Organic Substances

Organic chemists have discovered thousands of reactions by which organic compounds can be changed into different organic compounds. By using combinations of these reactions, chemical industries convert simple molecules from petroleum and natural gas into the large, complex organic molecules found in many useful products—including lifesaving drugs and many other consumer products as shown in **Figure 15.**

You have already read about substitution and condensation reactions. Two other important types of reactions by which organic compounds can be changed into different compounds are elimination reactions and addition reactions.

Figure 15 Many consumer products, such as plastic containers, fibers in ropes and clothing, and oils and waxes in cosmetics, are made from petroleum and natural gas.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Inquiry into Chemistry: Synthesizing Aspirin

Plan and carry out an investigation to demonstrate the stability and changes required to describe and predict chemical reactions, like aspirin.

Review the News

Obtain information from a current news story about new organic reactions. Evaluate your source and communicate your findings to the class.

Figure 16 Low-density polyethylene (LDPE) is made from gaseous ethene under high pressure in the presence of a catalyst. LDPE is used for playground equipment because it is easy to mold into various shapes, it is easy to dye into many colors, and it is durable. The name *polyethylene* comes from *ethylene*, which is the common name for ethene.

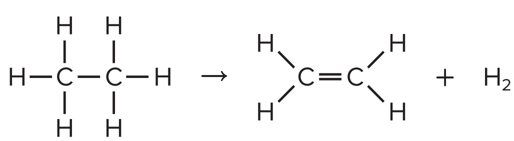
Elimination reactions

One way to change an alkane into a chemically reactive substance is to form a second covalent bond between two carbon atoms, producing an alkene. Forming double bonds from single bonds between carbon atoms is an **elimination reaction,** a reaction in which a combination of atoms is removed from two adjacent carbon atoms, forming an additional bond between them. The atoms that are eliminated usually form stable molecules, such as H_2O, HCl, or H_2.

Get It?

Define *elimination reaction* in your own words.

Ethene, the starting material for the playground equipment shown in **Figure 16,** is produced by the elimination of two hydrogen atoms from ethane. A reaction that eliminates two hydrogen atoms is called a **dehydrogenation reaction.** Note that since atoms are always conserved in a chemical reaction, the two hydrogen atoms form a molecule of hydrogen gas.



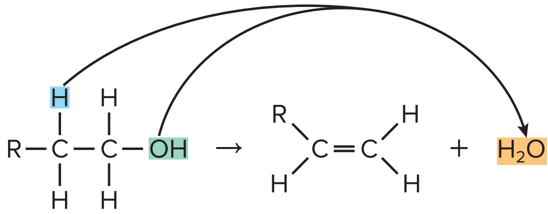
Ethane Ethene

Alkyl halides can undergo elimination reactions to produce an alkene and a hydrogen halide, as shown here.

$$\underset{\text{Alkyl halide}}{R{-}CH_2{-}CH_2{-}X} \rightarrow \underset{\text{Alkene}}{R{-}CH{=}CH_2} + \underset{\text{Hydrogen halide}}{HX}$$

Likewise, alcohols can also undergo elimination reactions by losing a hydrogen atom and a hydroxyl group to form water.

An elimination reaction in which the atoms removed form water is called a **dehydration reaction.** In the dehydration reaction, the alcohol is broken down into an alkene and water, as shown below.



Alcohol Alkene Water

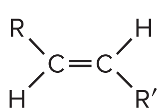
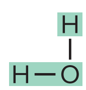
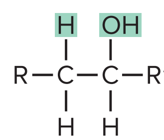
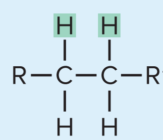
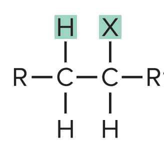
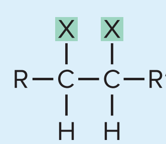
The generic form of this dehydration reaction can be written as follows.

$$R–CH_2–CH_2–OH \rightarrow R–CH=CH_2 + H_2O$$

Addition reactions

Another type of organic reaction appears to be an elimination reaction in reverse. An **addition reaction** results when other atoms bond to each of two atoms bonded by double or triple covalent bonds. Addition reactions typically involve the carbon atoms in the double bonds in alkenes or triple bonds in alkynes because molecules and ions that attract electrons can form bonds that use some of the electrons from the multiple bonds. Adding H_2O, H_2, HX, or X_2 to an alkene, as shown in **Table 12,** is common.

Table 12 Summary of Addition Reactions

Reactant Alkene	Addition Reactant	Product
	Water (hydration) 	Alcohol 
	Hydrogen (hydrogenation) H—H	Alkane 
	Hydrogen halide H—X	Alkyl halide 
	Halogen X—X	Alkyl dihalide 

A **hydration reaction,** also shown in **Table 12,** is an addition reaction in which a hydrogen atom and a hydroxyl group from a water molecule add to a double or triple bond. The generic equation shown in **Table 12** shows that a hydration reaction is the opposite of a dehydration reaction.

A reaction that involves the addition of hydrogen to atoms in a double or triple bond is called a **hydrogenation reaction.** One molecule of H_2 reacts to fully hydrogenate each double bond in a molecule. When H_2 adds to the double bond of an alkene, the alkene is converted to an alkane.

Get It?

Identify the reaction that is the reverse of a hydrogenation reaction.

Catalysts are usually needed in the hydrogenation of alkenes because the reaction's activation energy is too large without them. Catalysts such as powdered platinum or palladium provide a surface that adsorbs the reactants and makes their electrons more available to bond to other atoms. Hydrogenation reactions are commonly used to convert the liquid unsaturated fats found in oils from plants such as soybean, corn, and peanuts into saturated fats that are solid at room temperature. These hydrogenated fats are then used to make margarine and solid shortening.

Alkynes can also be hydrogenated to produce alkenes or alkanes. One molecule of H_2 must be added to each triple bond in order to convert an alkyne to an alkene, as shown here.

$$\text{R–C}\equiv\text{C–H} + \text{H}_2 \rightarrow \text{R–CH=CH}_2$$

After the first molecule of H_2 is added, the alkyne is converted to an alkene. A second molecule of H_2 follows the hydrogenation reaction.

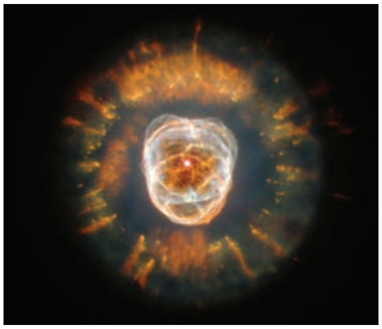
$$\text{R–CH=CH}_2 + \text{H}_2 \rightarrow \text{R–CH}_2\text{–CH}_3$$

In a similar mechanism, the addition of hydrogen halides to alkenes is an addition reaction useful to industry for the production of alkyl halides. The generic equation for this reaction is shown below.

$$\text{R–CH=CH–R}' + \text{HX} \rightarrow \text{R–CHX–CH}_2\text{–R}'$$

Real-World Chemistry

Polycyclic Aromatic Hydrocarbons (PAHs)



BIOLOGICAL MOLECULES Hydrocarbons composed of multiple aromatic rings are called PAHs. They have been found in meteorites and identified in the material surrounding dying stars. Scientists simulated conditions in space and found that about 10% of the PAHs were converted to alcohols, ketones, and esters. These molecules can be used to form compounds that are important in biological systems.

Oxidation-reduction reactions

Many organic compounds can be converted to other compounds by oxidation and reduction reactions. For example, suppose you want to convert methane, the main constituent of natural gas, to methanol, a common industrial solvent and raw material for making formaldehyde and methyl esters.

The conversion of methane to methanol can be represented by the equation shown in **Table 13,** in which [O] represents oxygen from an agent such as copper(II) oxide, potassium dichromate, or sulfuric acid. What happens to methane in this reaction? Before answering, it might be helpful to review the definitions of oxidation and reduction. Oxidation is the loss of electrons, and a substance is oxidized when it gains oxygen or loses hydrogen. Reduction is the gain of electrons, and a substance is reduced when it loses oxygen or gains hydrogen. Thus, methane is oxidized as it gains oxygen and is converted to methanol. Of course, every redox reaction involves both an oxidation and a reduction; however, organic redox reactions are described based on the change in the organic compound.

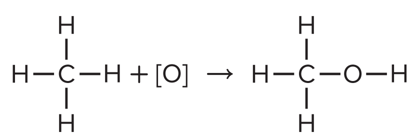
Oxidizing the methanol shown in **Table 13** is the first step in the sequence of reactions that can be used to produce an aldehyde, which are also shown in **Table 13.** For clarity, oxidizing agents are omitted. Preparing an aldehyde by this method is not always a simple task because the oxidation might continue, forming the carboxylic acid.

Get It?

Identify Use **Table 13** to identify two possible products that are produced when the aldehyde is further oxidized.

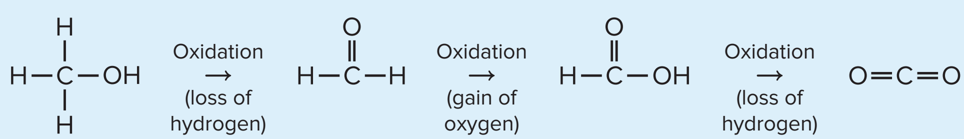
Table 13 Oxidation-Reduction Reactions

Oxidation of an alkane to an alcohol



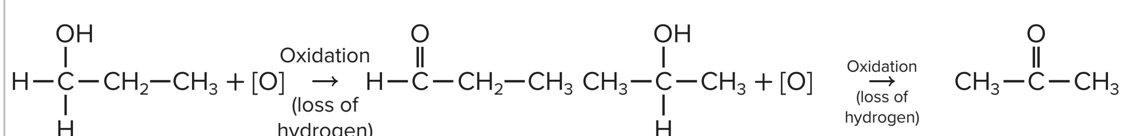
Methane   Methanol

A sequence of oxidation reactions



Methanol (methyl alcohol)   Methanal (formaldehyde)   Methanoic acid (formic acid)   Carbon dioxide

Oxidation of two isomers



1-Propanol   Propanal   2-Propanol   2-Propanone

However, not all alcohols can be oxidized to aldehydes and, subsequently, carboxylic acids. To understand why, compare the oxidations of 1-propanol and 2-propanol, shown in **Table 13.** Note that oxidizing 2-propanol yields a ketone, not an aldehyde. Unlike aldehydes, ketones resist further oxidation to carboxylic acids. Thus, while the propanal formed by oxidizing 1-propanol easily oxidizes to form propanoic acid, the 2-propanone formed by oxidizing 2-propanol does not react to form a carboxylic acid.

Get It?

Write the equation using molecular structures like those in **Table 13** for the formation of propanoic acid.

How important are organic oxidations and reductions? You have seen that oxidation and reduction reactions can change one functional group into another. That ability enables chemists to use organic redox reactions, in conjunction with the substitution and addition reactions you read about earlier in the module, to synthesize a tremendous variety of useful products. On a personal note, all living systems—including you—depend on the energy released by oxidation reactions. Of course, some of the most dramatic oxidation-reduction reactions are combustion reactions. All organic compounds that contain carbon and hydrogen burn in excess oxygen to produce carbon dioxide and water. For example, the highly exothermic combustion of ethane is described by the following thermochemical equation.

$$2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(l) \qquad \Delta H = -3120 \text{ kJ}$$

As you read previously, much of the world relies on the combustion of hydrocarbons as a primary source of energy. Our reliance on the energy from organic oxidation reactions is illustrated in **Figure 17.**

Predicting Products of Organic Reactions

The generic equations representing the different types of organic reactions you have learned—substitution, elimination, addition, oxidation-reduction, and condensation—can be used to predict the products of other organic reactions of the same types. For example, suppose you were asked to predict the product of an elimination reaction in which 1-butanol is a reactant. You know that a common elimination reaction involving an alcohol is a dehydration reaction.

Figure 17 People around the world depend on the oxidation of hydrocarbons to get to work and to transport products.

The generic equation for the dehydration of an alcohol is as follows.

$$R{-}CH_2{-}CH_2{-}OH \rightarrow R{-}CH{=}CH_2 + H_2O$$

To determine the actual product, first draw the structure of 1-butanol. Then use the generic equation as a model to see how 1-butanol would react.

The generic reaction shows that the –OH and a H– are removed from the carbon chain. Finally, draw the structure of the likely products, as shown in the following equation.

$$\underset{\text{1-Butanol}}{CH_3{-}CH_2{-}CH_2{-}CH_2{-}OH} \rightarrow \underset{\text{1-Butene}}{CH_3{-}CH_2{-}CH{=}CH_2} + H_2O$$

As another example, suppose that you wish to predict the product of the reaction between cyclopentene and hydrogen bromide. Recall that the generic equation for an addition reaction between an alkene and an alkyl halide is as follows.

$$R{-}CH{=}CH{-}R' + HX \rightarrow R{-}CHX{-}CH_2{-}R'$$

First, draw the structure for cyclopentene, the organic reactant, and add the formula for hydrogen bromide, the other reactant. From the generic equation, you can see that a hydrogen atom and a halide atom add across the double bond to form an alkyl halide. Finally, draw the formula for the likely product. The correct equation is as follows.

Cyclopentene   Hydrogen bromide   Bromocyclopentane

Check Your Progress

Summary

- Most reactions of organic compounds can be classified into one of five categories: substitution, elimination, addition, oxidation-reduction, and condensation.
- Knowing the types of organic compounds reacting can enable you to predict the reaction products.

Demonstrate Understanding

18. **Classify** each reaction as substitution, elimination, addition, or condensation.
    a. $CH_3CH{=}CHCH_2CH_3 + H_2 \rightarrow CH_3CH_2{-}CH_2CH_2CH_3$
    b. $CH_3CH_2CH_2\underset{\begin{array}{c}|\\ OH\end{array}}{C}HCH_3 \rightarrow CH_3CH_2CH{=}CHCH_3 + H_2O$
19. **Identify** the type of organic reaction that would best accomplish each conversion.
    a. alkyl halide → alkene
    b. alkene → alcohol
    c. alcohol + carboxylic acid → ester
    d. alkene → alkyl dihalide
20. **Complete** each equation by writing the condensed structural formula for the most likely product.
    a. $CH_3CH{=}CHCH_2CH_3 + H_2 \rightarrow$
    b. $CH_3CH_2\underset{\begin{array}{c}|\\ Cl\end{array}}{C}HCH_2CH_3 + OH^- \rightarrow$
21. **Predicting Products** Explain why the hydration reaction of 1-butene might yield two products, but the hydration reaction of 2-butene yields only one.

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LESSON 5

POLYMERS

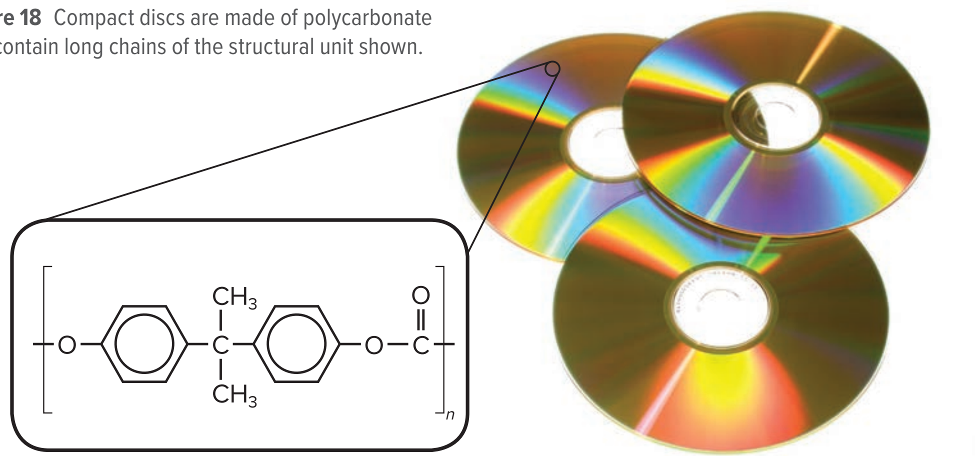
FOCUS QUESTION

Why are polymers so important for modern materials?

The Age of Polymers

The compact discs shown in **Figure 18** contain polycarbonate, which is made of extremely long molecules with groups of atoms that repeat in a regular pattern. This molecule is an example of a synthetic polymer. **Polymers** are large molecules consisting of many repeating structural units. In **Figure 18,** the letter *n* beside the structural unit of polycarbonate represents the number of structural units in the polymer chain. Because polymer *n* values vary widely, molecular masses of polymers range from less than 10,000 amu to more than 1,000,000 amu. A typical chain in nonstick coating on skillets has about 400 units, giving it a molecular mass of around 40,000 amu.

Figure 18 Compact discs are made of polycarbonate and contain long chains of the structural unit shown.



3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Laboratory: Polymerization Reactions
Obtain, evaluate, and communicate information to identify patterns in the chemical reactions that produce polymers and polyesters.

CCC **Identify Crosscutting Concepts**
Create a table of the crosscutting concepts and fill in examples you find as you read.

Before the development of synthetic polymers, people were limited to using natural substances such as stone, wood, metals, wool, and cotton. By the turn of the twentieth century, a few chemically treated natural polymers such as rubber and the first plastic, celluloid, had become available. Celluloid is made by treating cellulose from cotton or wood fiber with nitric acid.

The first synthetic polymer, synthesized in 1909, was a hard, brittle plastic called Bakelite. Because of its resistance to heat, it is still used today in stove-top appliances. Since 1909, hundreds of other synthetic polymers have been developed. Because of the widespread use of polymers, people might refer to this time as the Age of Polymers.

Reactions Used to Make Polymers

Polymers are relatively easy to manufacture. Polymers can usually be synthesized in one step in which the major reactant is a substance consisting of small, simple organic molecules called monomers. A **monomer** is a molecule from which a polymer is made.

When a polymer is made, monomers bond together one after another in a rapid series of steps. A catalyst is usually required for the reaction to take place at a reasonable pace. With some polymers, such as polyester fabric and nylon, two or more kinds of monomers bond to each other in an alternating sequence. A reaction in which monomer units are bonded together to form a polymer is called a **polymerization reaction.** The repeating group of atoms formed by the bonding of the monomers is called the structural unit of the polymer. The structural unit of a polymer made from two different monomers has the components of both monomers.

Low-density polyethylene (LDPE), which is synthesized by polymerizing ethene under pressure, is used to make children's toys and playground equipment, as shown in **Figure 19.** Ethene can also be made into ethylene glycol, which is the starting point for polyethylene terephthalate (PETE). PETE can be made into bottles or spun into fibers. As a fiber, it is called polyester.

Get It?
Compare and contrast a monomer and a structural unit of a polymer.

Figure 20 on the next page shows highlights of polymer development that led to the Age of Polymers. Although the first synthetic polymer was developed in 1909, the industry did not flourish until after World War II.

Figure 19 Polyethylene is a nontoxic, unbreakable polymer that is used to make toys and playground equipment for children.

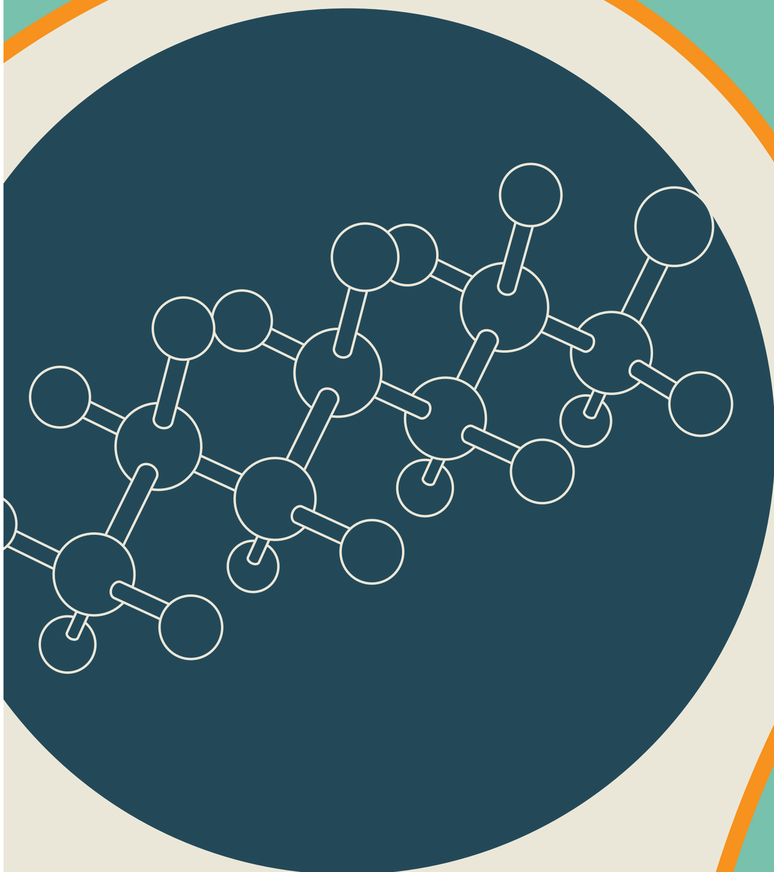


Figure 20

The Age of Polymers

Scientists working to understand the structure and properties of organic compounds have developed products that affect people everywhere. Their contributions helped usher in the Age of Polymers.

1 **1840s** Physicians begin using ether as an anesthetic during surgery.

2 **1865** The structure of benzene is proposed. It becomes the basis for the production of aromatic compounds.

3 **1899** Aspirin is widely distributed by physicians as a pain treatment.

4 **1909** The first plastic made from synthetic polymers, Bakelite, is developed.

5 **1939–1945** During World War II, nylon is allocated solely for military items such as parachutes, tents, and ponchos.

6 **1959** Spandex, an elastic fiber, is commercially produced.

7 **1988** The world's first polymer banknote is issued by the Reserve Bank of Australia. By 1996, all Australians use plastic money.

8 **2016** Researchers in Japan develop a new process for the self-assembly of polymer brushes. Polymer brushes coat the surface of a material and give it specific properties, such as low friction.

Addition polymerization

In **addition polymerization,** all of the atoms present in the monomers are retained in the polymer product. When the monomer is ethene, an addition polymerization results in the polymer polyethylene. Unsaturated bonds are broken in addition polymerization, just as they are in addition reactions. The difference is that the molecule added is a second molecule of the same substance, ethene. Note that the addition polymers in **Table 14** on the next page are similar in structure to polyethylene. That is, the molecular structure of each is equivalent to polyethylene in which other atoms or groups of atoms are attached to the chain in place of hydrogen atoms. All of these polymers are made by addition polymerization.

Get It?

Infer What must be present in a monomer that is used in an addition polymerization reaction?

Condensation polymerization

Condensation polymerization takes place when monomers containing at least two functional groups combine with the loss of a small by-product, usually water. Nylon and a type of bulletproof fabric are made this way. Nylon was first synthesized in 1931 and soon became popular because it is strong and can be drawn into thin strands resembling silk. Nylon 6,6 is the name of one type of nylon that is synthesized. One monomer is a chain with the end carbon atoms being part of carboxyl groups, as shown in **Figure 21.** The other monomer is a chain having amino groups at both ends. These monomers undergo a condensation polymerization that forms amide groups linking the subunits of the polymer, as shown by the tinted box in **Figure 19.** Note that one water molecule is released for every new amide bond formed.

$$\underset{\text{Adipic acid}}{n\mathrm{HOOC{-}(CH_2)_4{-}COOH}} + \underset{\text{1,6–Diamino hexane}}{n\mathrm{H_2N{-}(CH_2)_6{-}NH_2}} \rightarrow \underset{\text{Nylon 6,6}}{\left[\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}\mathrm{{-}(CH_2)_4{-}}\boxed{\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}\mathrm{{-}NH{-}}}\mathrm{(CH_2)_6{-}NH} \right]_n} + n\mathrm{H_2O}$$

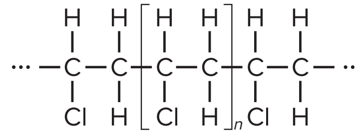
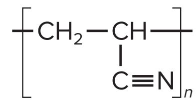
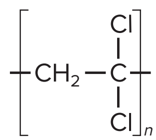
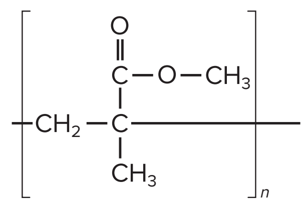
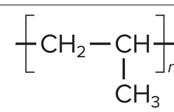
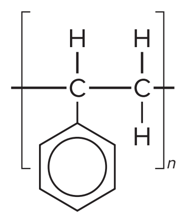
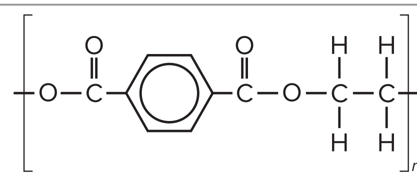
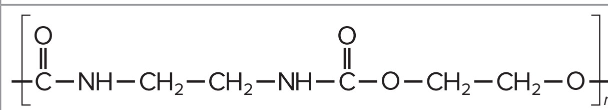
Figure 21 Nylon is a polymer consisting of thin strands that resemble silk.

STEM CAREER Connection

Organic Chemist

Are you intrigued by the wide range of molecules that contain carbon and the variety of chemical structures they have? Organic chemists study the properties and reactions of molecules that contain carbon. Sometimes they design new compounds that have unique properties. Some organic chemists work on applications for these new materials, such as pharmaceuticals or plastics. Organic chemists have at least a bachelor's degree in chemistry or a related field. Research jobs require a master's degree or Ph.D.

Table 14 **Common Polymers**

Polymer	Applications	Structural Unit
Polyvinyl chloride (PVC)	Plastic pipes, meat wrap, upholstery, rainwear, house siding, garden hose	 Polyvinyl chloride
Polyacrylonitrile	Fabrics for clothing and upholstery, carpet	
Polyvinylidene chloride	Food wrap, fabrics 	
Polymethyl methacrylate	“Nonbreakable” (acrylic glass) windows, inexpensive lenses, art objects 	
Polypropylene (PP)	Beverage containers, rope, netting, kitchen appliances	
Polystyrene (PS) and styrene plastic	Foam packing and insulation, plant pots, disposable food containers, model kits 	
Polyethylene terephthalate (PETE)	Soft-drink bottles, tire cord, clothing, recording tape, replacements for blood vessels	
Polyurethane	Foam furniture cushions, waterproof coatings, parts of shoes	

Properties and Recycling of Polymers

Why do we use so many different polymers today? One reason is that they are easy to synthesize. Another reason is that the starting materials used to make them are inexpensive. Still another, more important, reason is that polymers have a wide range of properties. Some polymers can be drawn into fine fibers that are softer than silk, while others are as strong as steel. Polymers do not rust like steel does, and many polymers are more durable than natural materials such as wood. Fencing, decking materials, and benches made of plastic, like the one shown in **Figure 22,** do not decay and do not need to be repainted.

Figure 22 Plastic lumber is made from recycled plastic, such as used soft-drink bottles, milk jugs, and other polyethylene waste.

Properties of polymers

Another reason why polymers are in such great demand is that it is easy to mold them into different shapes or to draw them into thin fibers. It is not easy to do this with metals and other natural materials because they must be heated either to high temperatures, do not melt at all, or are too weak to be used to form small, thin items.

As with all substances, polymers have properties that result directly from their molecular structure. For example, polyethylene is a long-chain alkane. Thus, it has a waxy feel, does not dissolve in water, is nonreactive, and is a poor electrical conductor. These properties make it ideal for use in food and beverage containers and as an insulator in electrical wire and TV cable.

Polymers fall into two different categories, based on their melting characteristics. A **thermoplastic** polymer is one that can be melted and molded repeatedly into shapes that are retained when cooled. Polyethylene and nylon are examples of thermoplastic polymers. A **thermosetting** polymer is one that can be molded when it is first prepared, but after it cools, it cannot be remelted. This property is explained by the fact that thermosetting polymers begin to form networks of bonds in many directions when they are synthesized. By the time they have cooled, thermosetting polymers have become, in essence, a single large molecule. Bakelite is an example of a thermosetting polymer. Instead of melting, Bakelite decomposes when overheated.

Get It?

Compare and contrast thermoplastic and thermosetting polymers.

Recycling polymers

The starting materials for the synthesis of most polymers are derived from fossil fuels. As the supply of fossil fuels becomes depleted, recycling plastics becomes more important. Recycling and buying goods made from recycled plastics decreases the amount of fossil fuels used, which conserves fossil fuels.

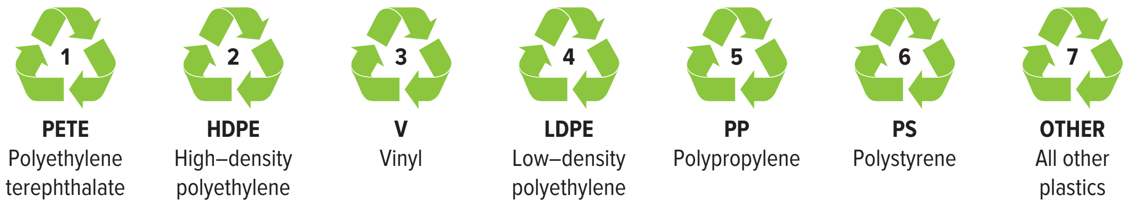


Figure 23 Codes on plastic products aid in recycling because they identify the composition of the plastic.

Currently, about 5% of the plastics used in the United States are recycled. Plastics recycling is difficult due to the large variety of polymers. Thermosetting polymers are more difficult to recycle than thermoplastic polymers because only thermoplastic materials can be melted and remolded repeatedly. Usually, the plastics must be sorted by composition. Separating plastics can be time-consuming and expensive. The standardized codes shown in **Figure 23** were developed by the plastics industry and the government to provide a quick way for recyclers to sort plastics.

Check Your Progress

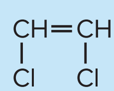
Summary

- Polymers are large molecules formed by combining smaller molecules called *monomers*.
- Polymers are synthesized through addition or condensation reactions.
- The functional groups present in polymers can be used to predict polymer properties.

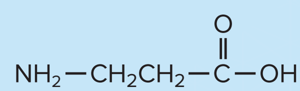
Demonstrate Understanding

22. **Draw** the structure for the polymer that could be produced from each of the following monomers by the method stated.

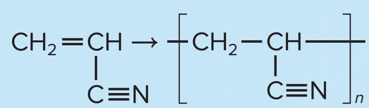
a. Addition



b. Condensation

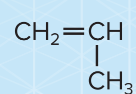


23. **Label** the following polymerization reaction as *addition* or *condensation*. Explain your answer.



24. **Identify** Synthetic polymers often replace stone, wood, metals, wool, and cotton in many applications. Identify some advantages and disadvantages of using synthetic materials instead of natural materials.

25. **Predict** the physical properties of the polymer that is made from the monomer shown. Mention solubility in water, electrical conductivity, texture, and chemical reactivity. Do you think it will be thermoplastic or thermosetting? Give reasons for your predictions.



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ENGINEERING & TECHNOLOGY

Promising New Plastics from Plant Polymers

Worldwide, about 300 billion kilograms of plastic are produced every year. Historically, plastics have been made from petroleum, a nonrenewable resource. But within the last few decades, new plastics have been developed that are made out of plant biomass. These plastics are called *bioplastics*. Some bioplastics are also biodegradable or compostable, in contrast with traditional plastics, which will not degrade for hundreds of years.

Biodegradable bioplastics reduce plastic pollution by using plants instead of petroleum.

Are Bioplastics Eco-Friendly?

Plastics are carbon-based polymers. They are versatile and useful materials, but making, using, and discarding plastics comes at a cost to the environment.

First, they are made from petroleum-based hydrocarbon polymers. Petroleum is a nonrenewable, limited resource that is becoming increasingly expensive. Second, plastic is extremely durable and persists for hundreds of years before breaking down. Plastic pollution is a pervasive problem, especially in Earth's oceans.

Bioplastics are a technology aimed at solving our dependence on petroleum. Bioplastics are made from plant-based polymers using crops such as corn or sugar cane, which are renewable. In addition, some bioplastics are compostable or biodegradable under the right conditions, such as polylactic acid (PLA), which can break down only at temperatures of 50°C or more.

If bioplastics are simply thrown away, another problem arises: when bioplastics break down in the oxygen-poor conditions found in landfills, they produce methane, a potent greenhouse gas. And if biodegradable bioplastics find their way into the recycling stream, they can contaminate the other plastics, making the recycled plastic unusable.

ENGAGE IN ARGUMENT FROM EVIDENCE

Research to find out more about the pros and cons of biodegradable bioplastics. Form teams to debate whether biodegradable bioplastics are better for the environment than traditional plastics made from petroleum.

STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 ALKYL HALIDES AND ARYL HALIDES

- The substitution of functional groups for hydrogen in hydrocarbons creates a wide variety of organic compounds.
- An alkyl halide is an organic compound that has one or more halogen atoms bonded to a carbon atom in an aliphatic compound.

- functional group
- halocarbon
- alkyl halide
- aryl halide
- plastic

Lesson 2 ALCOHOLS, ETHERS, AND AMINES

- Alcohols, ethers, and amines are formed when specific functional groups substitute for hydrogen in hydrocarbons.
- Because they readily form hydrogen bonds, alcohols have higher boiling points and higher water solubilities than other organic compounds.

- hydroxyl group
- alcohol
- denatured alcohol
- ether
- amine
- substitution reaction
- halogenation

Lesson 3 CARBONYL COMPOUNDS

- Carbonyl compounds are organic compounds that contain the C=O group.
- Five important classes of organic compounds containing carbonyl compounds are aldehydes, ketones, carboxylic acids, esters, and amides.

- carbonyl group
- aldehyde
- ketone
- carboxylic acid
- carboxyl group
- ester
- amide
- condensation reaction

Lesson 4 OTHER REACTIONS OF ORGANIC COMPOUNDS

- Most reactions of organic compounds can be classified into one of five categories: substitution, elimination, addition, oxidation-reduction, and condensation.
- Knowing the types of organic compounds reacting can enable you to predict the reaction products.

- elimination reaction
- dehydrogenation reaction
- dehydration reaction
- addition reaction
- hydration reaction
- hydrogenation reaction

Lesson 5 POLYMERS

- Polymers are large molecules formed by combining smaller molecules called *monomers*.
- Polymers are synthesized through addition or condensation reactions.
- The functional groups present in polymers can be used to predict polymer properties.

- polymer
- monomer
- polymerization reaction
- addition polymerization
- condensation polymerization
- thermoplastic
- thermosetting

THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

Where do natural and synthetic dyes get their colors?

CER Claim, Evidence, Reasoning

Explain your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

Based on Real Data*

SEP Data Analysis Lab

What are the optimal conditions to hydrogenate canola oil?

Because evidence suggests that *trans*-fatty acids are associated with increased risk of heart disease and cancer, the minimum amount of *trans*-fatty acids and the maximum amount of *cis*-oleic acid are desired in edible vegetable oils. Computer models were used to simulate processing conditions and to alter eight variables to optimize the output of the desirable oil. A small-scale industrial plant was then used to confirm the results of the computer simulation.

Data and Observations The table shows some of the data from this investigation.

CER Analyze and Interpret Data

1. **Calculate** the percent yield for each of the trials shown in the table.
2. **Claim** Which trial(s) produced the highest yield of *cis*-oleic acid and the lowest yield of *trans*-fatty acids?
3. **Evidence, Reasoning** Explain why the techniques used in this investigation are useful in manufacturing processes.

Data for Canadian Canola Oil

	Computer Simulation		Experimental	
Trial Run	*trans*-Fatty Acids (wt. %)	*cis*-Oleic Acid (wt. %)	*trans*-Fatty Acids (wt. %)	*cis*-Oleic Acid (wt. %)
1	4.90	69.10	5.80	70.00
2	4.79	63.75	4.61	64.00
3	4.04	68.96	4.61	67.00
4	5.99	62.80	7.10	65.00
5	4.60	68.10	5.38	66.50

*Data obtained from Izadifar, M. 2005. Application of genetic algorithm for optimization of vegetable oil hydrogenation process. *Journal of Food Engineering*. 78 (2007) 1–8.

THE CHEMISTRY OF LIFE

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THE CHEMISTRY OF LIFE

ENCOUNTER THE PHENOMENON

What molecules are essential to life?

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

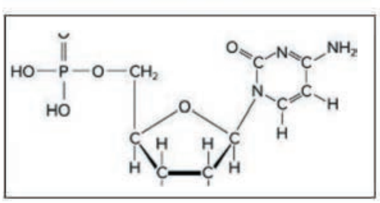
CER Claim, Evidence, Reasoning

Make Your Claim Use your CER chart to make a claim about what molecules are essential to life.

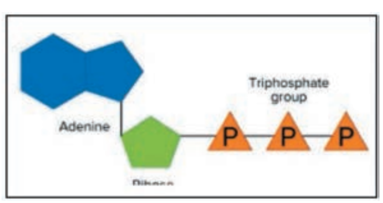
Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.



LESSON 4: Explore & Explain: Nucleic Acids



LESSON 5: Explore & Explain: ATP

LESSON 1

PROTEINS

FOCUS QUESTION

Why do you need to eat protein?

Protein Structure

Proteins are organic polymers made of amino acids linked together in a specific order. They are not just large, randomly arranged chains of amino acids. The functions and properties of proteins are closely related to the overall shapes of their molecular substructures. This means that for a protein to function properly, each protein must be folded into a specific three-dimensional structure. All living organisms, including the mountain goat and the plants shown in **Figure 1**, are composed of proteins.

Amino acids Many different functional groups are found in organic compounds. **Amino acids,** as their name implies, are organic molecules that have both an amino group and an acidic carboxyl group. The general structure is shown below.

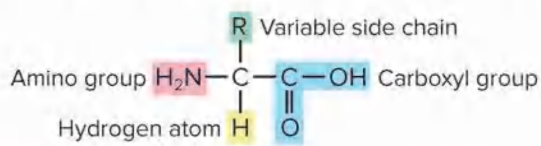


Figure 1 All living organisms contain proteins. A goat's hair and muscles are made up of structural proteins, as are the roots and leaves of plants.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

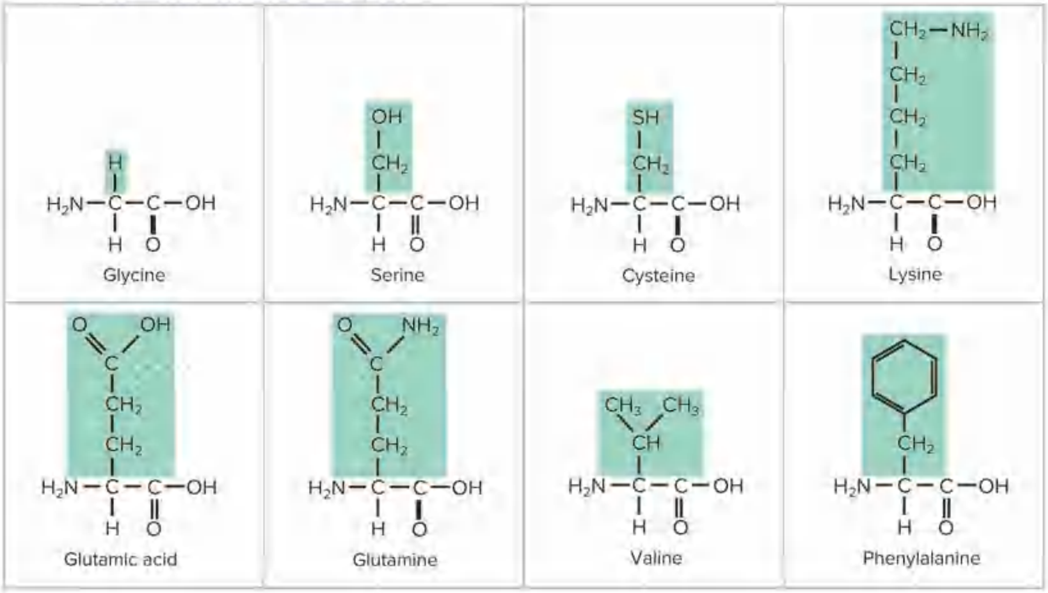
GO ONLINE to find these activities and more resources.

ChemLAB: Observe Temperature and Enzyme Action
Analyze and interpret data to determine the cause and effect of the chemical reactions responsible for the reactivity of enzymes at various temperatures.

Laboratory: Denaturation
Construct an explanation for the effect properties have on a protein before it undergoes denaturation.

Each amino acid has a central carbon atom around which four groups are arranged: an amino group ($-NH_2$), a carboxyl group ($-COOH$), a hydrogen atom, and a variable side chain, R, which can range from a hydrogen atom to a complex double-ring structure.

Table 1 **Amino Acid Examples**



Examine the different side chains of the amino acids shown in **Table 1.** Note how the different shapes of the molecules are controlled by specific side chains. Identify the nonpolar alkanes, polar hydroxyl groups, acidic and basic groups such as carboxyl and amino groups, aromatic rings, and sulfur-containing groups. This wide range of side chains and shapes is an important reason why proteins perform so many different functions.

The peptide bond The amino and carboxyl groups provide convenient bonding sites for linking amino acids together. Because an amino acid is both an amine and a carboxylic acid, two amino acids can combine to form an amide, releasing water in the process. Recall that it is possible to predict and describe what happens when two amino acids react based on the understanding of the chemical properties of the elements involved, and that atoms must be conserved. This reaction is a condensation reaction. As **Figure 2** shows, the *carboxyl* group of one amino acid reacts with the amino group of another amino acid to form an amide functional group.

Get It?

Explain how a peptide bond forms, and cite evidence that shows that during the reaction, the law of conservation of mass is observed.

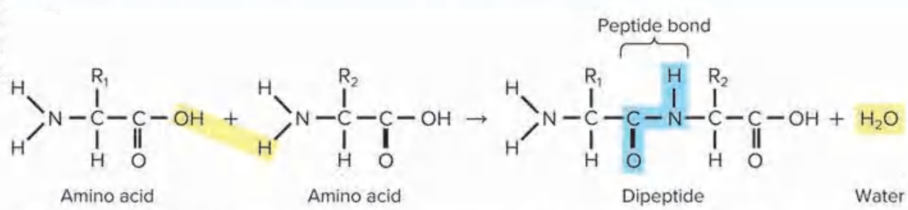


Figure 2 The amino group of one amino acid bonds to the carboxyl group of another amino acid to form a dipeptide and water. The organic functional group formed is an amide linkage called a peptide bond.

The amide bond that joins two amino acids, shown in **Figure 3**, is referred to as a **peptide bond.** A chain of two or more amino acids linked together by peptide bonds is called a **peptide.** A dipeptide is a molecule that consists of two amino acids. **Figure 4a** shows the structure of a dipeptide formed from the amino acids glycine (Gly) and phenylalanine (Phe). **Figure 4b** shows a different dipeptide, also formed by linking together Gly and Phe. The Gly-Phe is a different compound than Phe-Gly.

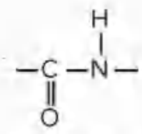


Figure 3 A peptide bond joins two amino acids to form a dipeptide.

The order in which amino acids are linked in a dipeptide is important. Here, each end of the two-amino-acid unit still has a free group—a free amino group on one end, and a free carboxyl group on the other end. Each of these groups can link to the opposite end of another amino acid, forming more peptide bonds. Living cells build peptides by adding amino acids to the carboxyl end of a growing chain.

Get It?

Cite evidence showing how the law of conservation of mass can be used to describe the formation of two similar compounds, yet form two functually different dipeptides from Gly and Phe amino acids. Describe how the molecular substructures differ.

Polypeptides

As peptide chains increase in length, other ways of referring to them become necessary. A chain of ten or more amino acids joined by peptide bonds is referred to as a polypeptide. When a chain reaches a length of about 50 amino acids, it is called a protein.

Because there are only 20 different amino acids that form proteins, it might seem reasonable to think that a small number of different protein structures are possible. However, a protein can have anywhere from 50 to more than a 1000 amino acids, arranged in any sequence. To calculate the number of possible sequences an amino acid can have, consider that each position on the chain can have one of 20 possible amino acids. For a peptide that has a total of n amino acids, there are 20^n possible sequences. So a dipeptide, with only two amino acids, can have 20^2, or 400, different possible amino acid sequences. Even the smallest protein, containing only 50 amino acids, has 20^{50}, or more than 1×10^{65}, possible arrangements of amino acids! It is estimated that human cells make between 80,000 and 100,000 different proteins. The wide range in structural arrangements explains why proteins can perform a vast array of functions.

Get It?

Calculate the possible number of sequences for a peptide chain comprised of four amino acids, and relate how the differences in molecular substructures for each sequence affects protein function.

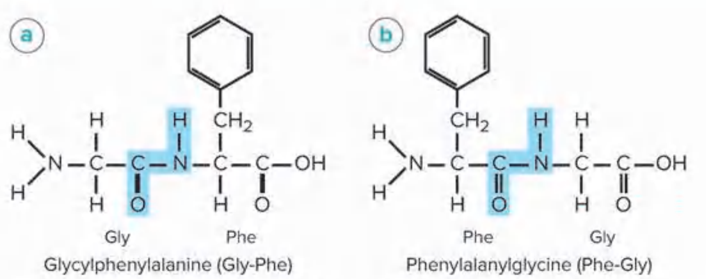


Figure 4 Glycine (Gly) and phenylalanine (Phe) can combine into two configurations.

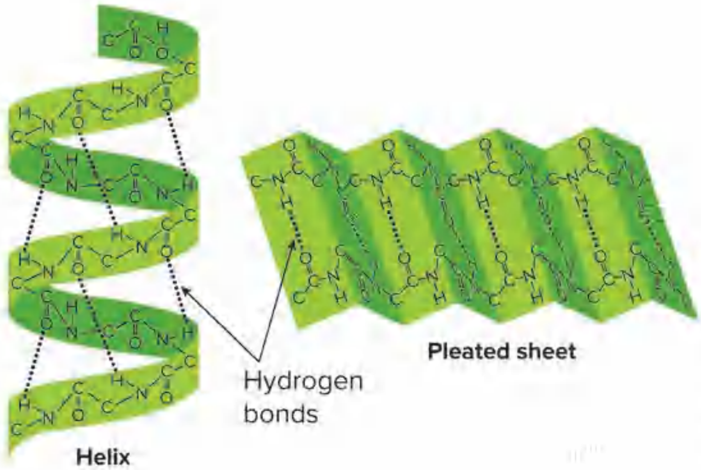


Figure 5 The folding of polypeptide chains into both helices and sheets involves amino acids in the chain held in position by hydrogen bonds. Other interactions among the various side chains are not shown here but play an important role in determining the three-dimensional shape of a polypeptide and its ultimate function.

Three-dimensional protein structure

The three-dimensional shape is determined by the interactions among the amino acids. Some areas of a polypeptide might twirl into helices, which are similar to the coils on a telephone cord. Other areas might bend back and forth repeatedly into a pleated sheet structure, like the folds of an accordion. A polypeptide chain might also fold back on itself and change direction. A given protein might have several helices, sheets, and turns, or none at all. **Figure 5** shows the folding patterns of a typical helix and a sheet. The overall three-dimensional shape of many proteins is globular—shaped like an irregular sphere. Other proteins have a long, fibrous shape. The shape is important to the function of the protein. If the shape of the protein changes, it might not be able to carry out its function in the cell.

Denaturation

Changes in temperature, ionic strength, pH, and other factors result in the unfolding and uncoiling of a protein. **Denaturation** is the process in which a protein's natural three-dimensional structure is disrupted. Cooking often denatures the proteins in foods. Because proteins function properly only when folded, denatured proteins are generally inactive.

The Many Functions of Proteins

Proteins play many roles in living cells. They are involved in speeding up chemical reactions, transport of substances, regulation of cellular processes, structural support of cells, communication within cells and among cells, cellular motion, and even serving as an energy source when other sources are scarce.

Speeding up reactions

In most organisms, the largest number of proteins function as enzymes, catalyzing the many reactions that occur in living cells. An **enzyme** is a biological catalyst. You read previously that a catalyst speeds up a chemical reaction without being consumed in the reaction.

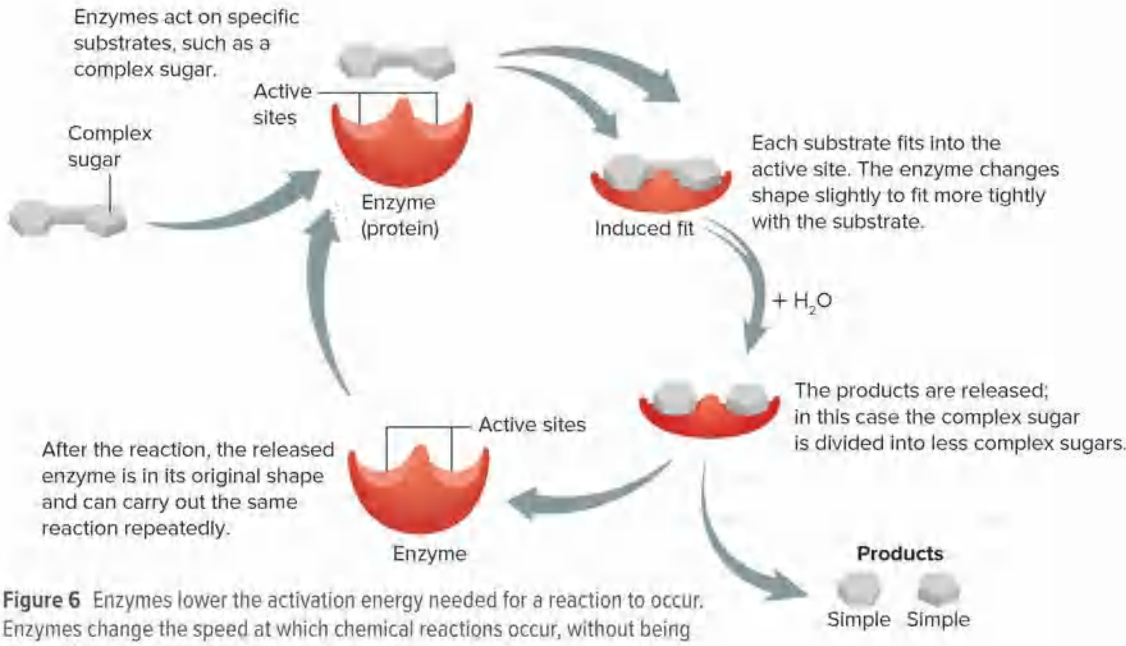


Figure 6 Enzymes lower the activation energy needed for a reaction to occur. Enzymes change the speed at which chemical reactions occur, without being altered themselves in the reaction, thus acting as a catalyst.

How do enzymes function?

The term **substrate** refers to a reactant in an enzyme-catalyzed reaction, as shown in **Figure 6**. Substrates bind to specific sites on enzyme molecules, usually pockets or crevices. This spot is called the **active site** of the enzyme. After the substrates bind to the active site, the site changes shape slightly to fit more tightly around the substrates. This recognition process is called induced fit. The shapes of the substrates must fit the shape of the active site, in the same way that puzzle pieces or a lock and key fit together.

The structure that forms when substrates are bound to an enzyme is called an enzyme-substrate complex. The large size of enzyme molecules allows them to form multiple bonds with their substrates. The large variety of amino acid side chains in the enzyme allows a number of different intermolecular forces to form. Recall that the attraction and repulsion of electrical forces within and between atoms explain the structure, properties, and transformations of matter. Intermolecular electrical forces between atoms lower the activation energy needed for breaking bonds, thus catalyzing reactions and reducing reaction rates.

Get It?

Describe in your own words how enzymes work.

Transport proteins

Figure 7 shows the protein hemoglobin, which carries oxygen in the blood from the lungs to the rest of the body. Other proteins combine with biological molecules called lipids to transport them from one part of the body to another through the bloodstream.

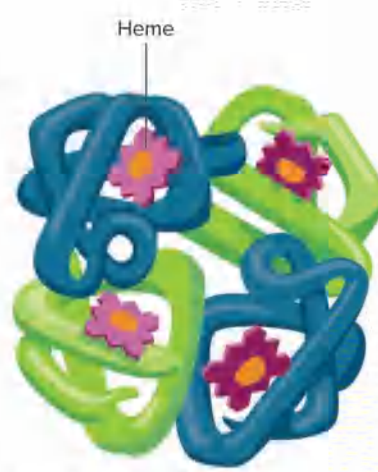


Figure 7 Hemoglobin is a globular protein with four peptide chains, each containing an iron group (called a heme) to which oxygen binds.

Structural support

The function of certain proteins is to form structures vital to organisms. These molecules are known as structural proteins. The most abundant structural protein in most animals is collagen, which is part of skin, ligaments, tendons, and bones. Other structural proteins make up feathers, fur, fingernails, and hair, as shown in **Figure 8.**

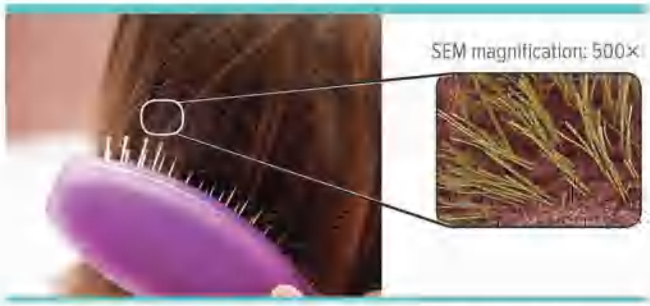


Figure 8 Human hair is made up of a fibrous structural protein called keratin.

Communication

Hormones are messenger molecules that carry signals from one part of the body to another. Some hormones are protein molecules. Insulin, a familiar example, is a relatively small (51 amino acids) protein hormone made by the cells of the pancreas.

When insulin is released into the bloodstream, the protein hormone signals body cells that blood sugar is abundant and should be stored. A lack of insulin in the human body over extended periods of time often results in diabetes, a disease that results when there is too much sugar in the bloodstream.

Check Your Progress

Summary

- The functions and properties of amino acids and proteins are closely related to their overall shape and molecular substructure.
- Proteins are biological polymers made of amino acids that are linked by peptide bonds.
- Protein chains fold into intricate three-dimensional structures.
- Proteins have many functions in the human body, including functions within cells, functions between cells, and functions of structural support.

Demonstrate Understanding

1. **Describe** three proteins and identify their functions.
2. **Compare** the structure of amino acids, dipeptides, polypeptides, and proteins. Which has the largest molecular mass? The smallest?
3. **Draw** the structure of the dipeptide Gly-Ser, circling the peptide bond.
4. **Evaluate** how the properties and funtions of proteins, including intermolecular electrical forces, make them such useful catalysts. How do they differ from other catalysts you have studied?
5. **Explain** how a change in temperature might affect a protein's structure and function.
6. **Categorize** Identify an amino acid from **Table 1** that can be classified in each of the categories in the following pairs.
   a. nonpolar side chain v. polar side chain
   b. aromatic v. aliphatic
   c. acidic v. basic

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LESSON 2

CARBOHYDRATES

FOCUS QUESTION

Why do you need to eat carbohydrates?

Kinds of Carbohydrates

Early observations that these compounds have the general formula $C_n(H_2O)_n$ and appear to be hydrates of carbon led to their being called *carbohydrates.* We now know that there are no full water molecules attached to carbohydrates, but the name has stayed. **Carbohydrates** are compounds that contain multiple hydroxyl groups (–OH) as well as a carbonyl functional group (C=O). These molecules range in size from single monomers to polymers made of thousands of monomer units. In living organisms, carbohydrates provide both immediate and stored energy. Foods rich in carbohydrates include pasta, milk, fruit, bread, and potatoes.

Monosaccharides

The simplest carbohydrates, often called simple sugars, are **monosaccharides.** Examples of monosaccharides are shown in **Figure 9.** Notice that they have a carbonyl group on one carbon and hydroxyl groups on most of the other carbons.

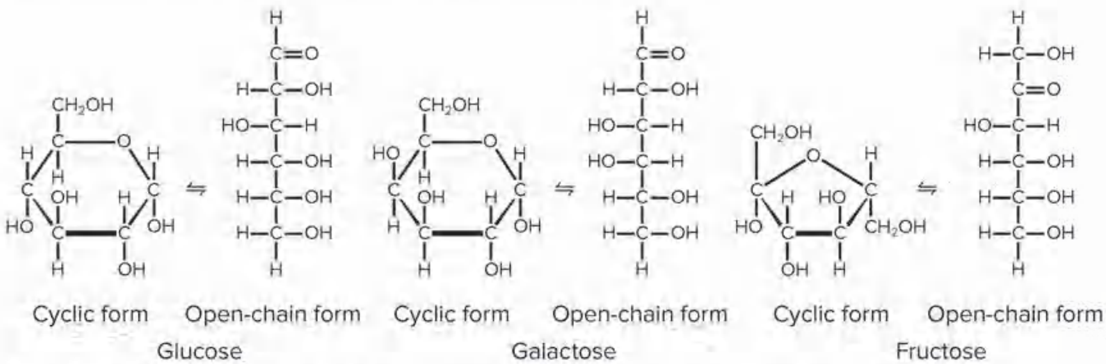

Figure 9 Glucose, galactose, and fructose are monosaccharides. In aqueous solutions, they exist in an equilibrium between their open-chain and cyclic forms.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Review the News

Obtain information from a current news story about the amount of carbohydrates we should include in our diets. Evaluate your source and communicate your findings to the class.

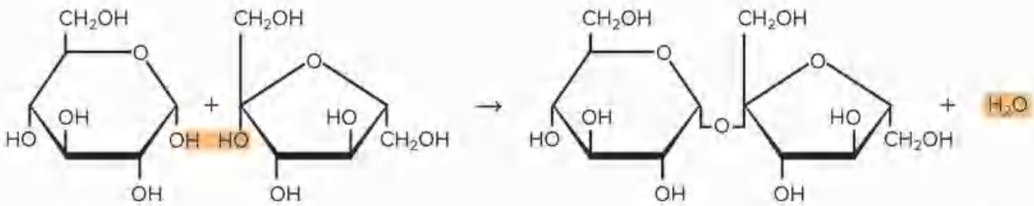

Figure 10 When glucose and fructose bond, the disaccharide *sucrose* forms. Note that water is also a product of this condensation reaction. Remember that each ring is made of carbon atoms and are not shown for simplicity.

The presence of a carbonyl group makes these compounds either aldehydes or ketones, depending on the location of the carbonyl group. Multiple polar groups make monosaccharides water-soluble and give them high melting points.

Glucose is a six-carbon sugar that has an aldehyde structure. Glucose is present in high concentrations in blood because it serves as the major source of immediate energy for the body. For this reason, glucose is often called blood sugar. Closely related to glucose is galactose, which differs only in how a hydroxyl group is oriented in space around one of the six carbon atoms. Fructose, or fruit sugar, is a six-carbon monosaccharide that has a ketone structure.

When monosaccharides are in aqueous solution, they exist as both open-chain and cyclic structures. The cyclic structures are more stable and are the predominant form of monosaccharides at equilibrium. Note in **Figure 9** that the carbonyl groups are present only in the open-chain structures. In the cyclic structures, they are converted to hydroxyl groups.

Disaccharides

Like amino acids, monosaccharides can be linked together by a condensation reaction in which water is released. When two monosaccharides bond together, a **disaccharide** is formed, as shown in **Figure 10.** The new bond formed is an ether functional group (C–O–C).

Sucrose is formed by the bonding of glucose and fructose. Lactose, found in milk, is formed when glucose and galactose bond. In plants, energy is stored in the form of sucrose. In animals, disaccharides are digested and broken down into simple sugars and used for energy.

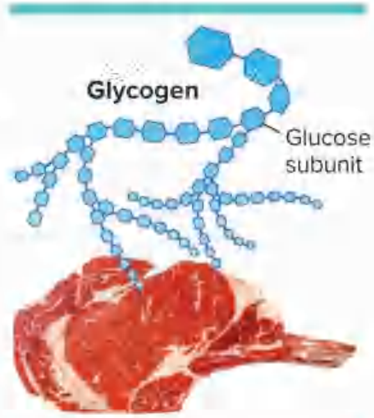

Figure 11 The glycogen found in the muscle and liver of animals is a polysaccharide made of glucose.

Polysaccharides

Another name for a complex carbohydrate is a **polysaccharide,** a polymer of simple sugars that contains 12 or more monomers, or subunits. The same type of bond that joins two monosaccharides in a disaccharide also links the monomers in a polysaccharide. Glycogen, shown in **Figure 11,** is a polysaccharide. It is composed of glucose subunits. It stores energy and is found mostly in the liver and muscles of humans and other animals.

Get It?

Explain the differences among a monosaccharide, a disaccharide, and a polysaccharide by citing evidence, including structural and functional differences, and where they occur in the natural world.

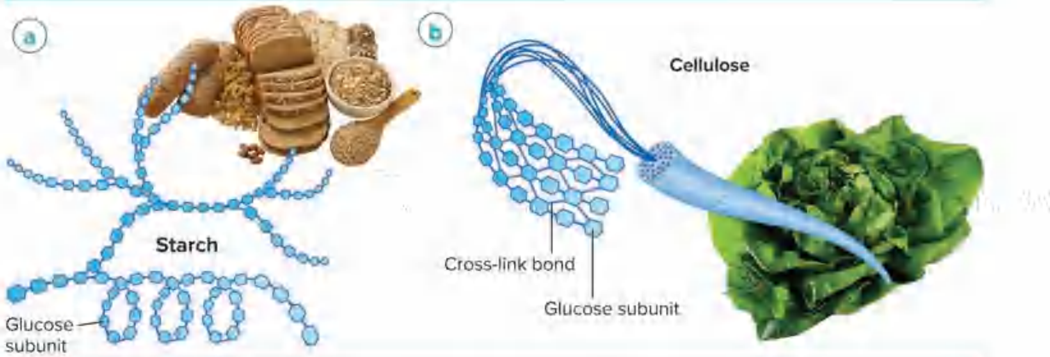

Figure 12 Two important polysaccharides are starch and cellulose. **a.** Starch molecules are branched or unbranched polymers. **b.** Cellulose is a linear, unbranched polymer that resembles a chain-link fence.

Plants contain polysaccharides in the form of starch and cellulose. The starch and cellulose structures in **Figure 12** show two distinct types, although both are solely composed of repeating glucose subunits that form polymers. As a result of these structural differences, they have different properties and functions. Although they are both water insoluble, starch is used by plants to store energy and cellulose is used to form rigid cell walls. The bonds that link the glucose subunits together are oriented differently in space. Because of this, humans cannot digest cellulose. Digestive enzymes cannot fit cellulose into their active sites.

Check Your Progress

Summary

- Carbohydrates are compounds that contain multiple hydroxyl groups (–OH) and a carbonyl functional group (C=O).
- Carbohydrates range in size from single monomers to polymers composed of hundreds or thousands of monomers.
- Monosaccharides in aqueous solution exist in both open-chain and cyclic structures.

Demonstrate Understanding

7. **Explain** how the functions of carbohydrates in living things reveal differences in molecular structure.
8. **Describe** the structures of monosaccharides, disaccharides, and polysaccharides. Which has the largest molecular mass? The smallest?
9. **Compare and contrast** the structures of starch and cellulose. How do the structural differences affect our ability to digest these two polysaccharides?
10. **Calculate** A carbohydrate has 2^n possible isomers, for n chiral carbon atoms in the structure. Calculate the number of possible isomers for galactose, glucose, and fructose.
11. **Interpret Scientific Illustrations** Research and draw a diagram of sucrose. Circle the ether functional group that bonds the monomer sugars.

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LESSON 3

LIPIDS

FOCUS QUESTION

Why do you need to eat fats?

What is a lipid?

A **lipid** is a large, nonpolar molecule. Because lipids are nonpolar, they are insoluble in water. In living organisms, lipids store energy efficiently, and make up most of the structure of cell membranes. Unlike proteins and carbohydrates, lipids are not polymers with repeating monomer subunits.

Fatty acids Many lipids have a major building block in common. This building block is the **fatty acid,** a long-chain carboxylic acid. Their structure is commonly represented as:

$$CH_3(CH_2)_nCOOH$$

Fatty acids are grouped into two main categories, depending on the presence or absence of double bonds between carbon atoms. Fatty acids that contain no double bonds are referred to as saturated. Those that have one or more double bonds are called unsaturated. The structures of two common fatty acids are shown in **Figure 13.**

Get It?

Identify the location of the bend in oleic acid on its structural formula.

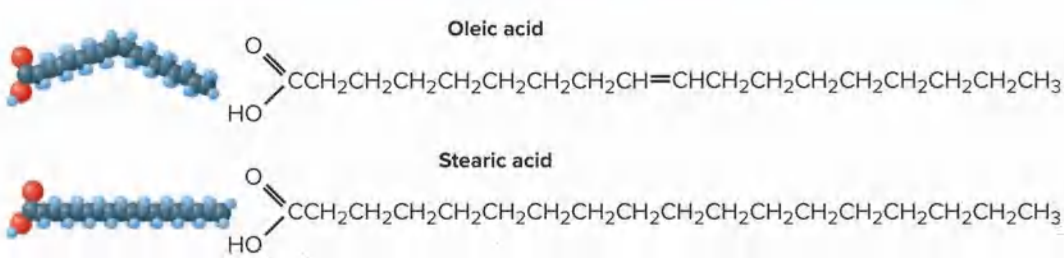

Figure 13 Two fatty acids found in many foods, including butter, are the 18-carbon unsaturated oleic acid and the 18-carbon stearic acid.

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COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Laboratory: Saturated and Unsaturated Fats

Construct an explanation for the proportion of the relative amount of saturated and unsaturated fatty acids in triglycerides.

Review the News

Obtain information from a current news story about the consequences of excess lipids in the body. Evaluate your source and communicate your findings to the class.

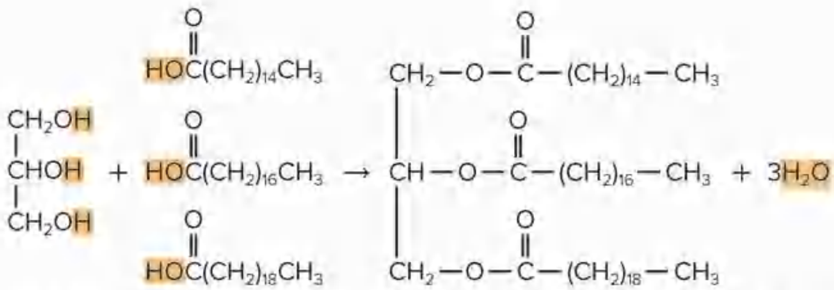

Figure 14 In a triglyceride, ester bonds are formed when the hydroxyl groups of glycerol combine with the carboxyl groups of the fatty acids.

An unsaturated fatty acid can become saturated if it reacts with hydrogen. As you read previously, hydrogenation is an addition reaction in which hydrogen gas reacts with carbon atoms that are linked by multiple bonds. Each unsaturated carbon atom can pick up one hydrogen atom to become saturated.

The double bonds in naturally occurring fatty acids are almost all in the *cis* geometric isomer form. The *cis* isomer has identical groups oriented on the same side of the molecule around a double bond. Because of the *cis* orientation, unsaturated fatty acids have a kink, or bend, in their structure that prevents them from packing together. They do not form as many intermolecular attractions as saturated fatty acid molecules and have weaker intermolecular forces between molecules than saturated fatty acids. Recall that intermolecular attractions can affect properties of matter at the bulk scale. As a result, unsaturated fatty acids have lower melting points and can occur as liquids at room temperature.

Triglycerides

Although fatty acids are abundant in living organisms, they are rarely found alone. They are most often found bonded to glycerol, a molecule with three carbons, each containing a hydroxyl group. When three fatty acids are bonded to a glycerol backbone through ester bonds, a **triglyceride** is formed. The formation of a triglyceride is shown in **Figure 14.** Triglycerides can be either solids or liquids at room temperature, as shown in **Figure 15.** If liquid, they are usually called oils. If solid at room temperature, they are called fats.

Figure 15 Most mixtures of triglycerides from plant sources are liquids because the triglycerides contain unsaturated fatty acids. Animal fats contain larger proportions of saturated fatty acids. They are usually solids at room temperature.

Get It?

Describe how intermolecular forces affect the structure and properties of fatty acids.

CCC CROSSCUTTING CONCEPTS

Structure and Function Construct a table that compares and contrasts how molecular structures affect the function and properties of triglyceride fats and oils. Evidence should include molecular structure, bonding, melting points, packing arrangements, and intermolecular forces.

STEM CAREER Connection

Chemical Engineer

If you are curious about what things are made of, where they occur in nature, or how they can be made in the lab, you could be a chemical engineer. They use principles of chemistry and other sciences to solve problems that involve the production of chemicals, fuel, drugs, food, and many other products. You will need a Bachelor's Degree to work as a chemical engineer.

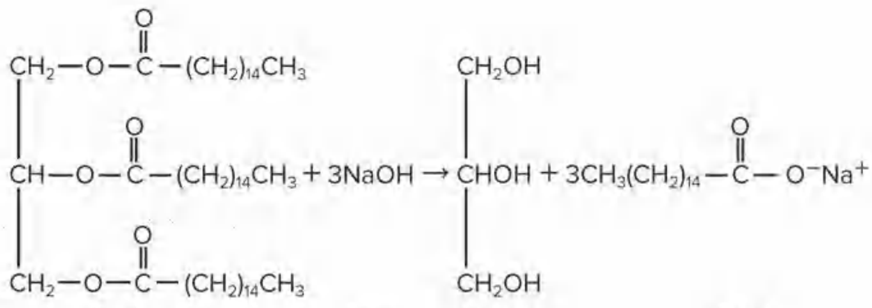

Figure 16 Soap forms by the reaction of a triglyceride and a strong base.

Fatty acids are stored in the fat cells of your body as triglycerides. When energy is abundant, fat cells store the excess energy in the fatty acids of triglycerides. When energy is scarce, the cells break down the triglycerides, releasing the energy used to form them.

Although enzymes break down triglycerides in living cells, the reaction can be duplicated outside of cells by using a strong base, such as sodium hydroxide. This reaction—the hydrolysis of a triglyceride using an aqueous solution of a strong base to form carboxylate salts and glycerol—is **saponification,** as shown in **Figure 16.** Saponification is used to make soaps, which are usually the sodium salts of fatty acids. A soap molecule has both a polar end and a nonpolar end. Soaps are used with water to clean nonpolar dirt and oil because the nonpolar dirt and oil bond to the nonpolar end of the soap molecules, and the polar end of the soap molecules is soluble in water. Thus, the dirt-laden soap molecules that have now interacted with the dirt and oil can be rinsed away with the water.

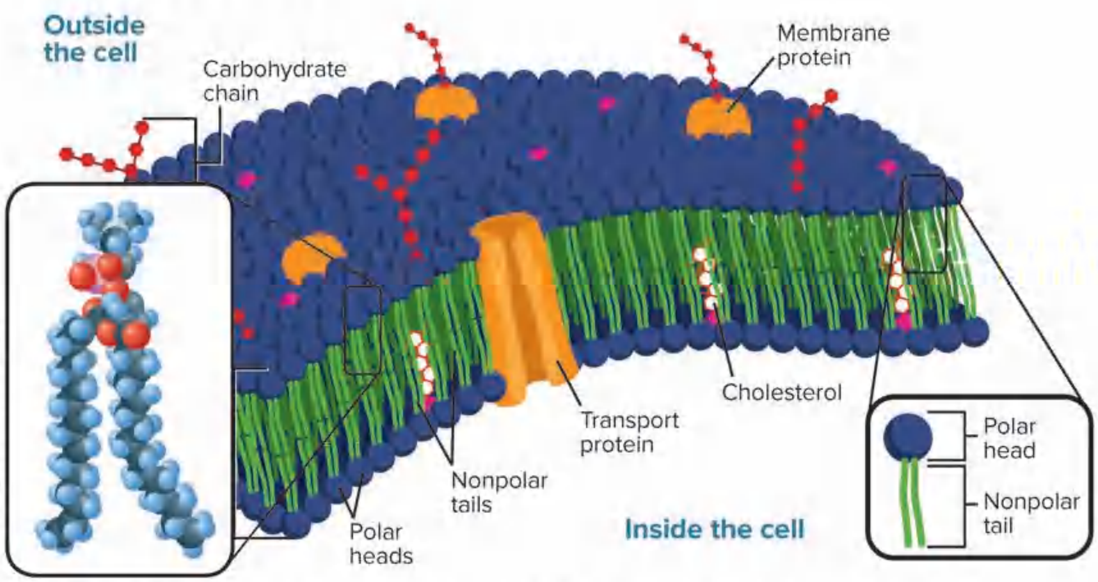

Figure 17 A phospholipid has a polar head and two nonpolar tails. The membranes of living cells are formed by a double layer of lipids, called a bilayer. The polar heads are on the outer and inner perimeter of the membrane and the tails are on the inside of the bilayer.

Phospholipids

Another important type of triglyceride, a phospholipid, is found in greatest abundance in cellular membranes. A **phospholipid** is a triglyceride in which one of the fatty acids is replaced by a polar phosphate group. As shown in **Figure 17** on the previous page, the polar part of the molecule forms a head and the nonpolar fatty acids look like tails. A typical cellular membrane has two layers of phospholipids, which are arranged with their nonpolar tails pointing inward and their polar heads pointing outward. This arrangement is called a lipid bilayer. Because the lipid bilayer structure acts as a barrier, the cell is able to regulate the materials that enter and leave through the membrane.

BIOLOGY Connection Investigations of how venom functions as a catalyst in breaking down cell membranes show how scientific understandings rely on detailed examinations of different components in a system, including molecular substructures and interactions on an atomic scale. These types of studies show that the venom of poisonous snakes contain a class of enzymes known as phospholipases. These enzymes catalyze the breakdown of phospholipids. The venom of the eastern diamond-back rattlesnake contains a phospholipase that hydrolyzes the ester bond at the middle carbon of phospholipids. If the larger of the two breakdown products of this reaction gets into the bloodstream, it dissolves the membranes of red blood cells, causing them to rupture. Because the venom destroys the blood cells, it is referred to as a hemotoxic venom. (The prefix *hemo-* indicates blood.) A bite from the eastern diamondback can lead to death if it is not treated immediately.

Figure 18 Plants produce a wax that coats their leaves. The wax protects the leaves from drying out.

Waxes

Another type of lipid, wax, also contains fatty acids. A **wax** is a lipid that is formed by combining a fatty acid with a long-chain alcohol. The general structure of these soft, solid fats with low melting points is shown below, with *x* and *y* representing variable numbers of CH_2 groups.

$$CH_3(CH_2)_x - \overset{\overset{\displaystyle O}{\|}}{C} - O - (CH_2)_y CH_3$$

Both plants and animals make waxes. Plant leaves are often coated with wax, which prevents water loss. Notice in **Figure 18** how raindrops bead up on the leaves of a plant, indicating the presence of the waxy layer. The honeycombs that bees make are also made of a wax, commonly called beeswax. Combining the 16-carbon fatty acid palmitic acid and a 30-carbon alcohol chain makes a common form of beeswax. Candles are sometimes made of beeswax because it tends to burn slowly and evenly.

Polyethylene and polypropylene waxes are used in many industrial applications. One such application is in the form of release agents in molds that allow a material to be removed without bonding to the surface of the mold. The wax provides a barrier that prevents the molding material from bonding, allowing for the easy removal of the material from the mold. Without this barrier, the molding material would adhere to the mold, making it impossible for the mold and the material to be separated.

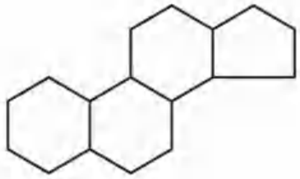

Figure 19 This Giant Marine toad uses a steroid toxin called *bufotoxin* as a defense mechanism. The toxin is fatal to some animals, including dogs and cats.

Steroids

Not all lipids contain fatty acid chains. **Steroids** are lipids that have multiple cyclic rings in their structures. All steroids are built from the basic four-ring steroid structure shown above.

Some hormones, such as many sex hormones, are steroids that function to regulate metabolic processes. Cholesterol, another steroid, is an important structural component of cell membranes. Vitamin D also contains the four-ring steroid structure and plays a role in the formation of bones. The Giant Marine toad, *Bufo marinus*, shown in **Figure 19,** uses a steroid called *bufotoxin* as a defense mechanism. The toad secretes the toxin from warts on its back and from glands just behind the eye.

Check Your Progress

Summary

- The properties and functions of lipids are related to molecular structure, bonding, and inter-molecular forces on an atomic scale.
- Fatty acids are long-chain carboxylic acids that usually have between 12 and 24 carbon atoms.
- Saturated fatty acids have no double bonds; unsaturated fatty acids have one or more double bonds.
- Fatty acids can be linked to glycerol backbones to form triglycerides.
- Steroids are lipids that have multiple-ring structures.

Demonstrate Understanding

12. **Describe** the function of lipids.
13. **Describe** the structures of fatty acids, triglycerides, phospholipids, and steroids.
14. **List** an important function of each of these types of lipids.
    a. triglycerides
    b. phospholipids
    c. waxes
    d. steroids
15. **Identify** two reactions that fatty acids undergo.
16. **Describe** how the function of cell membranes relates to their molecular structure.
17. **Compare and contrast** the structures of a steroid, a phospholipid, and a wax.
18. **Write** the equation for the complete hydrogenation of the polyunsaturated fatty acid linoleic acid, $CH_3(CH_2)_4CH{=}CH(CH_2)CH{=}CH(CH_2)_7COOH$.
19. **Interpret Scientific Illustrations** Draw the general structure of a phospholipid. Label the polar and nonpolar portions of the structure.

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LESSON 4
NUCLEIC ACIDS

FOCUS QUESTION
What is DNA?

Structure of Nucleic Acids

Nucleic acids are the information-storage molecules of the cell. This group of molecules got its name from the location in which they are primarily found—the nucleus. It is from this control center of cells that nucleic acids carry out their major functions. A **nucleic acid** is a nitrogen-containing biological polymer that is involved in the storage and transmission of genetic information. The monomer that makes up a nucleic acid is called a **nucleotide.** Each nucleotide has three parts: an inorganic phosphate group, a five-carbon monosaccharide sugar, and a nitrogen-containing structure called a nitrogenous base, shown in **Figure 20a.** The phosphate group is the same in all nucleotides, but the sugar and the nitrogen base vary.

In a nucleic acid, the sugar of one nucleotide is bonded to the phosphate of another nucleotide, as shown in **Figure 20b.** Thus, the nucleotides are strung together in a chain, or strand, containing alternating sugar and phosphate groups. Each sugar is also bonded to a nitrogen base that sticks out from the chain. The nitrogen bases on adjoining nucleotide units are stacked one above the other in a slightly askew position, much like the steps in a staircase. This orientation is shown in **Figure 20b.** Also note in **Figure 20b** (far right) that intermolecular forces hold each nitrogen base close to the nitrogen bases above and below it.

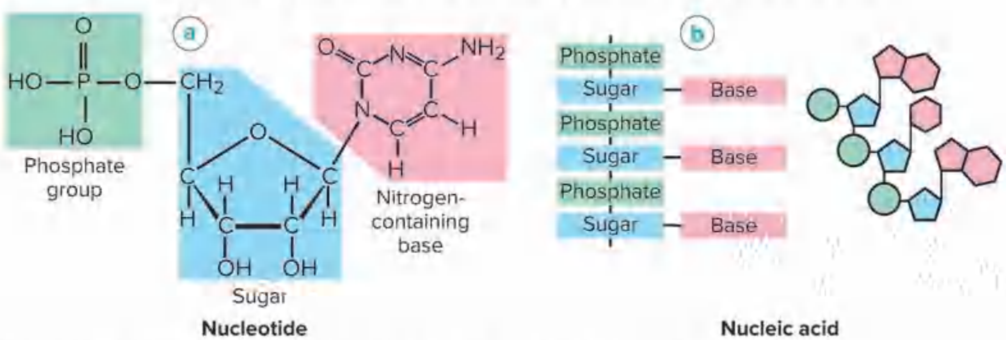

Figure 20 Nucleotides are the monomers from which nucleic acid polymers are formed.

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COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

CCC **Identify Crosscutting Concepts**
Create a table of the crosscutting concepts and fill in examples you find as you read.

Revisit the Encounter the Phenomenon Question
What information from this lesson can help you answer the module question?

DNA: The Double Helix

You have heard of DNA (deoxyribonucleic acid), a nucleic acid found in living cells. DNA contains the master plans for building all the proteins in an organism's body.

The structure of DNA

DNA consists of two long chains of nucleotides wound together to form a spiral structure, as shown in **Figure 21.** Each nucleotide in DNA contains a phosphate group, the five-carbon sugar deoxyribose, and a nitrogenous base. The alternating sugar and phosphate groups in each chain make up the outside, or backbone, of the spiral structure. The nitrogen bases are on the inside of the structure. Because the spiral structure is composed of two chains, it is known as a double helix.

Figure 21 The structure of DNA is a double helix that resembles a twisted zipper. The two sugar-phosphate backbones form the outsides of the zipper.

DNA contains four different nitrogenous bases: adenine (A), thymine (T), cytosine (C), and guanine (G). As **Figure 22** shows, both adenine and guanine contain a double ring. Thymine and cytosine are single-ring structures. Looking again at **Figure 22,** notice that each nitrogen base on one strand of the helix is oriented next to a nitrogen base on the opposite strand, in the same way that the teeth of a zipper are oriented. A zipper analogy is often used because when DNA replicates it comes apart along this zipper, resulting in the separation of the double helix into two strands. The side-by-side base pairs are close enough so that hydrogen bonds form between them. Because each nitrogen base has a unique arrangement of organic functional groups that can form hydrogen bonds, the nitrogen bases always pair in a specific way so that the optimum number of hydrogen bonds form. As **Figure 22** shows, guanine always binds to cytosine, and adenine always binds to thymine. The G–C and A–T pairs are called complementary base pairs.

Get It?

Describe how intermolecular electrical charges and hydrogen bonding are related to the arrangement of nitrogen bases within the DNA structure.

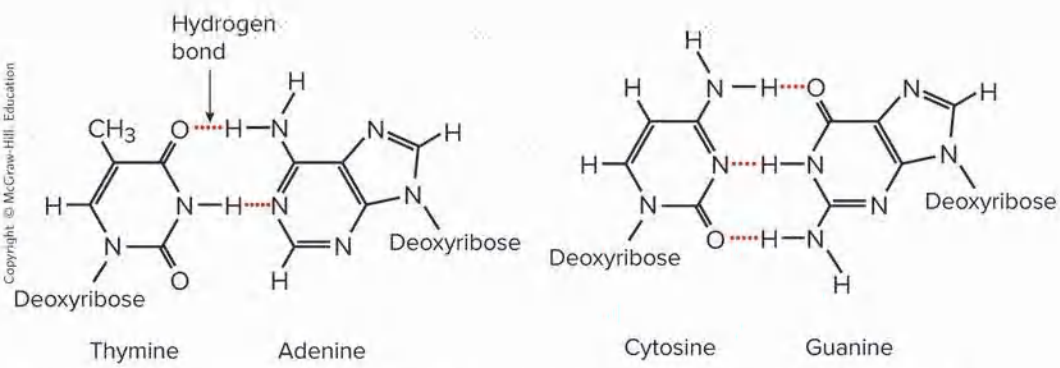

Figure 22 In DNA, base pairing exists between a double-ringed base and a single-ringed base. Adenine and thymine always pair, forming two hydrogen bonds between them. Guanine and cytosine always form three hydrogen bonds when they pair.

Because of complementary base pairing, the amount of adenine in a molecule of DNA always equals the amount of thymine, and the amount of cytosine always equals the amount of guanine. It is because of this complementary pairing that DNA is able to replicate itself in preparation for the next generation of cells. The first stage in DNA replication involves the unwinding of the double strand of DNA and the breaking of the hydrogen bonds between bases to produce two separated strands. Each strand then serves as a template where new nucleotides form hydrogen bonds with their complementary bases on each of the single DNA strands. Because each nitrogen base always combines with their complimentary base, the pattern of complementary base pairs is replicated, resulting in the formation of an exact copy of the original DNA strand. The strands then rewind, to form a new DNA molecule which is now identical to the initial one.

The function of DNA

In 1953, James Watson and Francis Crick used the observation of complementary pairing to make one of the greatest scientific discoveries of the twentieth century when they determined the double-helix structure of DNA. Watson and Crick used their model to predict how DNA's chemical structure enables it to function. Before the cell divides, the DNA is copied so that the new generation of cells gets the same genetic information. Having determined that the two chains of the DNA helix are complementary, Watson and Crick realized that these patterns provide a mechanism by which the genetic material of a cell is copied. They accomplished this feat without performing many laboratory experiments themselves. Instead they analyzed and synthesized the work of numerous scientists who had carefully carried out studies on DNA.

The four nitrogenous bases of DNA serve as the letters of the alphabet in the information-storage language of living cells. The specific sequence of these letters represents an organism's master instructions, just as the sequence of letters in the words of this sentence convey special meaning. The sequence of bases is different in every species of organism, allowing for an enormous diversity of life-forms—all from a language that uses only four letters. It is estimated that the DNA in a human cell has about three billion complementary base pairs, arranged in a sequence unique to humans.

RNA

RNA (ribonucleic acid) is also a nucleic acid. Its general structure differs from that of DNA in three important ways, as shown in **Figure 23** on the next page. First, as you have read, DNA contains the nitrogen bases adenine, cytosine, guanine, and thymine. RNA contains adenine, cytosine, guanine, and uracil. Thymine is never found in RNA. Second, RNA contains the sugar ribose. DNA contains the sugar deoxyribose, which has a hydrogen atom in place of a hydroxyl group at one position.

The third difference between DNA and RNA is a result of these structural differences. DNA is normally arranged in a double helix in which hydrogen bonding links the two chains together through their bases. RNA is usually single-stranded, with no such hydrogen bonds forming among the bases.

Get It?

Describe how the patterns observed in nucleotide base arrangements are used to make a replica of a DNA strand.

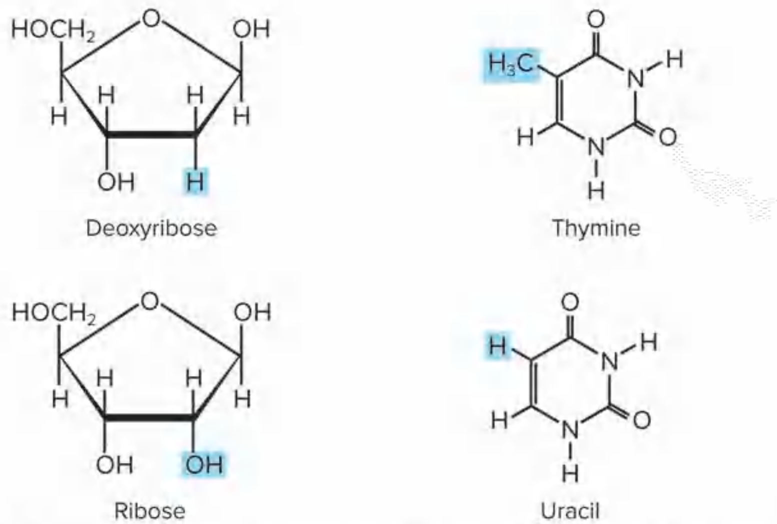

Figure 23 DNA and RNA differ in their components. The two structures on the left are found in DNA. The two structures on the right are found in RNA.

Whereas DNA functions to store genetic information, RNA allows cells to use the information found in DNA. You have read that the genetic information of a cell is contained in the sequence of nitrogen bases in the DNA molecule. Cells use this base sequence to make RNA with a corresponding sequence. The RNA is then used to make proteins, each with an amino-acid sequence that is determined by the order of nitrogen bases in RNA. The sequences of bases are referred to as the genetic code. Because proteins are the molecular tools that carry out most activities in a cell, the DNA double helix is ultimately responsible for controlling the thousands of chemical reactions that take place in cells.

Check Your Progress

Summary

- Nucleic acids are polymers of nucleotides, which consist of a nitrogen base, a phosphate group, and a sugar.
- DNA and RNA are the information-storage molecules of a cell.
- DNA is double stranded, and RNA is single stranded.
- The molecular structure of DNA reveals how it replicates itself due to its double-helix shape and its pattern of complimentary pairing of nucleotides.

Demonstrate Understanding

20. **Explain** the primary function of RNA and DNA.
21. **Identify** the specific structural components of both RNA and DNA.
22. **Relate** the function of DNA to its structure.
23. **Relate** the function of RNA to its structure.
24. **Analyze** the structure of nucleic acids to determine what structural feature makes them acidic.
25. **Describe** how intermolecular electrical forces and hydrogen bonding give nucleotides their unique function in complementary base pairing and how these base pair patterns lead to DNA replication.

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LESSON 5
METABOLISM

FOCUS QUESTION

How do you get energy from the food you eat?

Anabolism and Catabolism

The set of chemical reactions that occur within an organism is its **metabolism.** Why are so many reactions involved in metabolism? Living organisms must accomplish two major functions in order to survive. They have to extract energy from nutrients in forms that they can use immediately as well as store for future use. In addition, they have to use nutrients to make building blocks for synthesizing all of the molecules needed to perform their life functions. These processes are summarized in **Figure 24.**

The term **catabolism** refers to the metabolic reactions that break down complex biological molecules such as proteins, polysaccharides, triglycerides, and nucleic acids for the purposes of forming smaller building blocks and extracting energy. After you eat a meal of spaghetti and meatballs, your body immediately begins to break down the starch polymer in the pasta into glucose. The glucose is then broken down into smaller molecules in a series of energy-releasing catabolic reactions. Meanwhile, the protein polymers in the meatballs are catabolized into amino acids.

These complex molecules are broken down by a series of enzyme-catalyzed reactions that convert food into usable energy that drives bodily processes critical to survival.

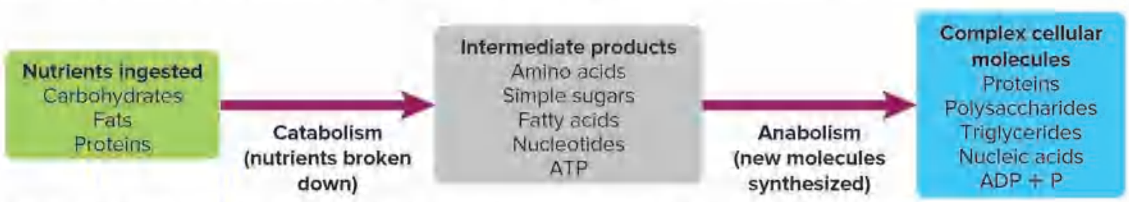

Figure 24 A large number of different metabolic reactions take place in living cells. Some involve breaking down nutrients to extract energy; these are catabolic processes. Others involve using energy to build large biological molecules; these reactions are anabolic processes.

Describe *Choose one food that you ate recently, and describe how it was metabolized.*

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COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Inquiry into Chemistry: Urinalysis

Plan and carry out an investigation to determine the flow, cycle, and conservation of energy and matter in the human body.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the module question?

Anabolism refers to the metabolic reactions that use energy and small building blocks to synthesize the complex molecules needed by an organism. After your body has extracted the energy from food, it uses that energy and the amino-acid building blocks produced from the meat proteins to synthesize the proteins that allow your muscles to contract, catalyze metabolic reactions, and perform many other functions in your body.

Figure 24 on the previous page, shows the relationship between catabolism and anabolism. The nutrients listed on the left side of the diagram are broken down into intermediate products. These intermediate products are used as building blocks for the products listed on the right side of the diagram.

Get It?
Explain how the terms *metabolism*, *catabolism*, and *anabolism* are related.

ATP

Catabolism and anabolism are linked by common chemical building blocks that catabolic reactions produce and anabolic reactions use. A common form of potential chemical energy also links the two processes, as shown in **Figure 25.** The nutrient breakdown and subsequent formation of newly synthesized molecules represents not only how matter flows through a system, but also energy. **ATP** (adenosine triphosphate) is a nucleotide that functions as the universal energy-storage molecule in living cells.

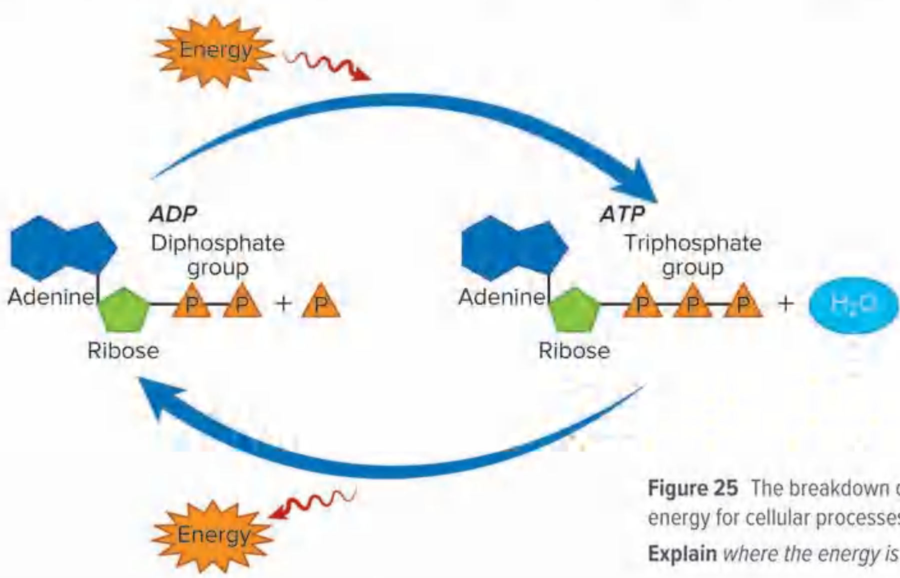

Figure 25 The breakdown of ATP provides energy for cellular processes in living organisms.
Explain *where the energy is stored in ATP.*

ACADEMIC VOCABULARY

conceptualize
to visualize or conceive an abstract idea in the mind
The atomic cloud model is hard to conceptualize.

CCC CROSSCUTTING CONCEPT

Energy and Matter Use **Figures 24** and **25** to create a concept map to conceptualize how changes in energy and matter are conserved in a metabolic system. Describe the system in terms of how matter and energy flow through the system.

During catabolic reactions, cells harness the chemical energy of foods and store it in the bonds of ATP. When these bonds are broken, the chemical energy is released and used by cells to drive anabolic reactions that might not otherwise occur. Most cellular reactions have an efficiency of only about 40% at best; the remaining 60% of the energy in food is lost as heat, which your body uses to keep warm. During catabolic reactions, cells produce ATP by adding an inorganic phosphate group to the nucleotide adenosine diphosphate (ADP) in an endothermic reaction. One mole of ATP stores approximately 30.5 kJ of energy under normal cellular conditions. During anabolism, the reverse reaction occurs. ATP is broken down to form ADP and inorganic phosphate in an exothermic reaction. Approximately 30.5 kJ of energy is released from each mole of ATP.

Get It?

Describe what occurs when ATP becomes ADP.

Photosynthesis

What is the source of energy that fuels metabolism? For most living things, including the grass shown in **Figure 26,** certain wavelengths of sunlight provide this energy. We know that energy cannot be created or destroyed, so what happens to light energy after it has been captured by photosynthetic organisms? Some bacteria and the cells of all plants and algae are able to convert light energy into chemical energy. This process is called **photosynthesis,** where energy is transformed into molecular bond energy found in carbohydrates. During photosynthesis, carbon dioxide and water yield a carbohydrate (glucose) and oxygen gas. The following net reaction takes place during photosynthesis.

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} + \text{light energy} \rightarrow \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

Photosynthesis results in the reduction of the carbon atom in carbon dioxide as glucose is formed. During this redox process, oxygen atoms in water are oxidized to oxygen gas.

Figure 26 Grass and other green plants use certain wavelengths of sunlight as an energy source. Other living organisms, such as cows, obtain energy by eating plants or eating other organisms that eat plants.

Cellular Respiration

Most organisms need oxygen to live, survive, and thrive in their environment. The oxygen produced during photosynthesis is used by living things during the process of **cellular respiration,** the process in which glucose is broken down to form carbon dioxide and water, while releasing large amounts of energy. This energy is then further transported from one place to another within an organism during cellular respiration. Cellular respiration is the major energy-producing process in living organisms.

Figure 27 Swimmers need large amounts of energy when they compete in a race. This energy is stored in the bonds of ATP in their cells.

Unlike photosynthetic organisms, animals cannot capture light energy and must obtain their energy by consuming glucose-containing sources, such as plants or other animals. This energy is then stored in the bonds of ATP. **Figure 27** shows one use of energy in the body. Cellular respiration is a redox process; the carbon atoms in glucose are oxidized while oxygen atoms in oxygen gas are reduced to the oxygen in water. The net reaction that takes place during cellular respiration is as follows. Note, as stated earlier, that the energy produced during cellular respiration has an efficiency of only 40%, with the majority of energy lost as heat.

$$\underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2} \rightarrow \underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} + \text{energy}$$

The net reaction for cellular respiration looks amazingly familiar; it is the reverse of the net equation for photosynthesis.

Fermentation

During cellular respiration, glucose is completely oxidized, and oxygen gas is required to act as the oxidizing agent. Cells can extract energy from glucose in the absence of oxygen, but not nearly as efficiently. Without oxygen, only a fraction of the chemical energy of glucose can be released. Whereas cellular respiration produces 38 mol of ATP for every 1 mol of glucose catabolized in the presence of oxygen, only 2 mol of ATP are produced per mole of glucose that is catabolized in the absence of oxygen. This provides enough energy for oxygen-deprived cells so that they do not die. The process by which glucose is broken down in the absence of oxygen is known as **fermentation.** There are two common kinds of fermentation. In one, ethanol and carbon dioxide are produced. In the other, lactic acid is produced.

Get It?

Compare and contrast how energy is transported or flows within plants and animals from one place to another, and how the flow of energy can be transferred between living systems.

Alcoholic fermentation

Yeast and some bacteria can ferment glucose to produce the alcohol ethanol.

$C_6H_{12}O_6$	$\rightarrow$	$2CH_3CH_2OH$	+	$2CO_2$	+	energy
Glucose		Ethanol		Carbon dioxide		

This reaction is important in producing some foods, as shown in **Figure 28**. Alcoholic fermentation is needed to make bread dough rise, form tofu from soybeans, and produce the ethanol in alcoholic beverages.

Figure 28 Carbon dioxide formed during fermentation, leaves holes in the bread. These holes give bread a light, less-dense texture.

Lactic acid fermentation

During strenuous activity, muscle cells often use oxygen faster than it can be supplied by the blood. When the supply of oxygen is depleted, cellular respiration stops.

$C_6H_{12}O_6$	$\rightarrow$	$2CH_3CH(OH)COOH$	+	energy
Glucose		Lactic acid		

The lactic acid that is produced is moved from the muscles through the blood to the liver. However, if lactic acid builds up in muscle cells at a faster rate than the blood can remove it, muscle fatigue results. An immediate burning sensation and soreness a few days later is an indication that lactic acid was produced.

Check Your Progress

Summary

- In living systems, such as plants and animals, energy is not created or destroyed. It is transported and can flow from one place to another within a system and can also flow or be transferred between systems.
- Living organisms undergo catabolism and anabolism.
- Photosynthesis directly or indirectly provides almost all living things with energy.
- The net equation for cellular respiration is the reverse of the net equation for photosynthesis.

Demonstrate Understanding

26. **Explain** why metabolism is important to living cells.
27. **Compare and contrast** the process of anabolism and catabolism.
28. **Explain** how metabolic processes demonstrate how energy and matter are conserved in living systems for humans and other animals.
29. **Compare and contrast** the processes of photosynthesis, cellular respiration, and fermentation.
30. **Determine** whether each process is anabolic or catabolic.
    a. photosynthesis
    b. cellular respiration
    c. fermentation
31. **Evaluate** Why is it necessary to use sealed casks when making wine?
32. **Calculate** How many moles of ATP would a yeast cell produce if 6 mol of glucose were oxidized completely in the presence of oxygen? How many moles of ATP would the yeast cell produce from 6 mol of glucose if the cell were deprived of oxygen?

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SCIENTIFIC BREAKTHROUGHS

Antibiotics from Amphibians

Researchers are pursuing an interesting source of new substances that can fight bacteria—frog skin! Antibiotics are substances that kill bacteria. Some are produced naturally, and others are synthetic. Overuse of some antibiotics has caused the development of resistant strains of bacteria. These resistant bacteria are no longer vulnerable to antibiotics that were previously effective. For that reason, scientists are always on the lookout for new antibiotics.

This foothill yellow-legged frog is one of the many species of frogs that secrete substances that might provide the basis of new antibiotics.

What are the secretions made of?

Scientists analyzing substances secreted through the skin of frogs have found many substances with potential applications in fighting bacterial infection.

The secretions from frog skin contain polypeptides. Recall that a polypeptide is a chain of amino acids joined by peptide bonds.

Research Challenges

Researchers have no intention of using frogs to produce the actual antibiotics. Instead, frog skin is analyzed, and the structures of effective polypeptide secretions are identified, with the goal of synthesizing copies. There are several advantages to this plan.

First, it keeps frogs from being removed from their ecosystems. This is important because many amphibian populations worldwide are threatened or endangered.

Second, the secretions found on frog skins are often too aggressive to use in their natural form. When this occurs, the polypeptides are adjusted to keep human cells from being destroyed along with the bacteria.

OBTAIN, EVALUATE, AND COMMUNICATE INFORMATION

Work with a partner to do additional research using a variety of sources on the search for new antibiotics. Carefully evaluate the information you find. Then, write a paragraph communicating what you have learned.

STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 PROTEINS

- Proteins are biological polymers made of amino acids that are linked by peptide bonds.
- Protein chains fold into intricate three-dimensional structures.
- Proteins have many functions in the human body, including functions within cells, functions between cells, and functions of structural support.

- protein
- amino acid
- peptide bond
- peptide
- denaturation
- enzyme
- substrate
- active site

Lesson 2 CARBOHYDRATES

- Carbohydrates are compounds that contain multiple hydroxyl groups (–OH) and a carbonyl functional group (C=O).
- Carbohydrates range in size from single monomers to polymers composed of hundreds or thousands of monomers.
- Monosaccharides in aqueous solution exist in both open-chain and cyclic structures.

- carbohydrate
- monosaccharide
- disaccharide
- polysaccharide

Lesson 3 LIPIDS

- Fatty acids are long-chain carboxylic acids that usually have between 12 and 24 carbon atoms.
- Saturated fatty acids have no double bonds; unsaturated fatty acids have one or more double bonds.
- Fatty acids can be linked to glycerol backbones to form triglycerides.
- Steroids are lipids that have multiple-ring structures.

- lipid
- fatty acid
- triglyceride
- saponification
- phospholipid
- wax
- steroid

Lesson 4 NUCLEIC ACIDS

- Nucleic acids are polymers of nucleotides, which consist of a nitrogen base, a phosphate group, and a sugar.
- DNA and RNA are the information-storage molecules of a cell.
- DNA is double stranded, and RNA is single stranded.

- nucleic acid
- nucleotide

Lesson 5 METABOLISM

- Living organisms undergo catabolism and anabolism.
- Photosynthesis directly or indirectly provides almost all living things with energy.
- The net equation for cellular respiration is the reverse of the net equation for photosynthesis.

- metabolism
- catabolism
- anabolism
- ATP
- photosynthesis
- cellular respiration
- fermentation

THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

What molecules are essential to life?

CER Claim, Evidence, Reasoning

Explain your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

SEP Data Analysis Lab

How does DNA replicate?

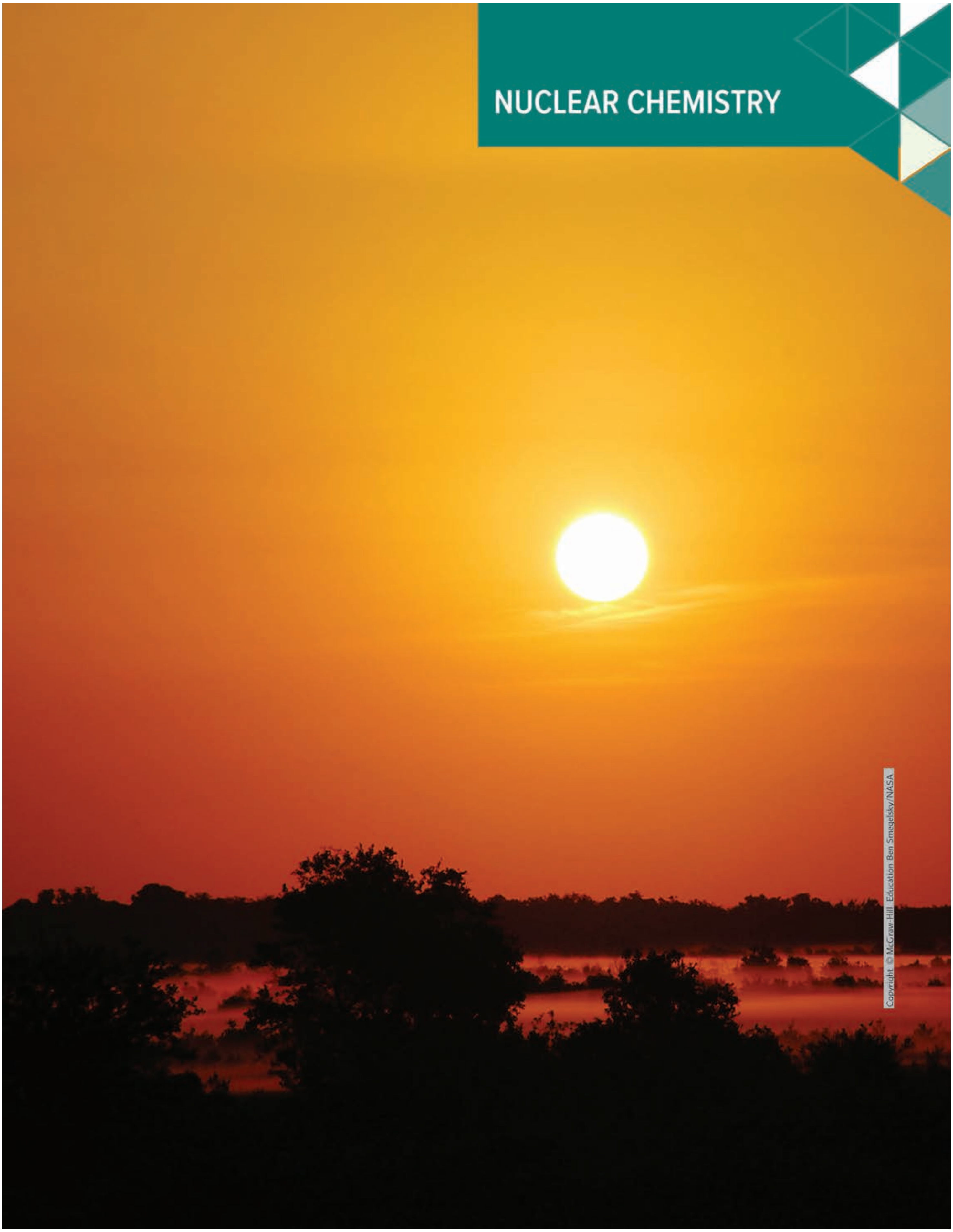
DNA replicates before a cell divides so that each of the two newly formed cells has a complete set of genetic instructions.

Data and Observations When DNA begins to replicate, the two nucleotide strands start to unzip. An enzyme breaks the hydrogen bonds between the nitrogenous bases. Other enzymes deliver free nucleotides to the exposed nitrogenous bases, adenine hydrogen-bonding with thymine and cytosine with guanine. Thus, each strand builds a complementary strand by base-pairing with free nucleotides. When the free nucleotides have been hydrogen-bonded into place, their sugars and phosphates bond covalently to those on adjacent nucleotides to form the new backbone.

CER Analyze and Interpret Data

1. **Develop a model** that shows the base pairing in DNA replication.
2. **Claim, Evidence, Reasoning** If in your model the original DNA segments are colored red and the free nucleotides are colored blue, what pattern of colors will the newly replicated DNA segments have? Will all new segments have the same color pattern? Explain.

NUCLEAR CHEMISTRY



NUCLEAR CHEMISTRY

ENCOUNTER THE PHENOMENON

Where does the Sun get all its energy?

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

CER Claim, Evidence, Reasoning

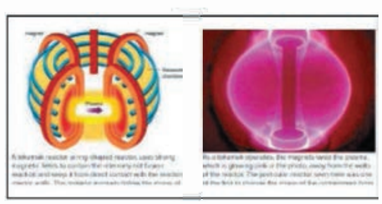
Make Your Claim Use your CER chart to make a claim about where the sun gets all its energy.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.

LESSON 1: Explore & Explain: Defining Radioactivity



LESSON 3: Explore & Explain: Nuclear Fusion

LESSON 1

NUCLEAR RADIATION

FOCUS QUESTION

How was radioactivity discovered?

The Discovery of Radioactivity

You have studied various forms of chemical reactions. In any chemical reaction, atoms can gain, lose, or share valence electrons, but the identity of the atoms does not change. Nuclear reactions, which you will study in this chapter, are different. Nuclear chemistry is concerned with the structure of atomic nuclei and the changes they undergo. Whereas chemical reactions involve only small energy changes, nuclear reactions involve much larger energy changes. **Table 1** offers a comparison of chemical reactions and nuclear reactions.

Table 1 Comparison of Chemical and Nuclear Reactions

Chemical Reactions		Nuclear Reactions	
	• Occur when bonds are broken and formed • Involve only valence electrons • Associated with small energy changes • Atoms keep the same identity although they might gain, lose, or share electrons, and form new substances • Temperature, pressure, concentration, and catalysts affect reaction rates		• Occur when nuclei combine, split, and emit radiation • Can involve protons, neutrons, and electrons • Associated with large energy changes • Atoms of one element are often converted into atoms of another element • Temperature, pressure, and catalysts do not normally affect reaction rates

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Review the News

Obtain information from a current news story about nuclear processes, including fusion and fission of unstable nuclei. Evaluate your source and communicate your findings to the class.

In 1895, German physicist Wilhelm Roentgen (1845–1923) found that invisible rays were emitted when electrons bombarded the surface of certain materials. These invisible rays caused photographic plates to darken, and Roentgen named these high-energy emissions X-rays. At that time, French physicist Henri Becquerel (1852–1908) was studying minerals that emit light after being exposed to sunlight, a phenomenon called phosphorescence. Building on Roentgen's work, Becquerel wanted to determine whether phosphorescent minerals also emitted X-rays.

Becquerel discovered by chance that phosphorescent uranium salts produced spontaneous emissions that darkened photographic plates. He observed this phenomenon even when the uranium salts were not exposed to light. Chemist Marie Curie (1867–1934) and her husband Pierre Curie (1859–1906) took Becquerel's mineral sample, called pitchblende, and isolated the components emitting the rays. They concluded that the darkening of the photographic plates was due to rays emitted from the uranium atoms present in the mineral sample. Marie Curie named the process by which materials give off such rays radioactivity; the rays and particles emitted by a radioactive source are called radiation. **Figure 1** shows the darkening of photographic film that is exposed to radiation emitted by radium salts.

The work of Marie and Pierre Curie was extremely important in establishing the origin of radioactivity and developing the field of nuclear chemistry. In 1898, the Curies identified two new elements, polonium and radium, on the basis of their radioactivity. Henri Becquerel and the Curies shared the 1903 Nobel Prize in Physics for their work. Marie Curie also received the 1911 Nobel Prize in Chemistry for her work with polonium and radium. The 1911 prize honored her achievement in discovering those elements, as well as isolating radium and contributing substantially to chemical knowledge through her study of its properties and compounds.

Get It?

Explain what Marie and Pierre Curie concluded about the darkening of the photographic plates.

Figure 1 Radium salts are placed on a special emulsion on a photographic plate. After the plate is developed, the emulsion shows the dark tracks left by radiation emitted by the radium salts.

Table 2 **Properties of Alpha, Beta, and Gamma Radiation**

Property	Alpha Radiation	Beta Radiation	Gamma Radiation
Symbol	α	β	γ
Composition	alpha particles	beta particles	high-energy electromagnetic radiation
Description of radiation	helium nuclei, $^{4}_{2}He$	electrons	photons
Charge	2+	1–	0
Mass	6.64×10^{-27} kg	9.11×10^{-31} kg	0
Approximate energy	5 MeV	0.05 to 1 MeV	1 MeV
Relative penetrating power	blocked by paper	blocked by metal foil	not completely blocked by lead or concrete

Types of Radiation

Recall that isotopes are atoms of the same element that have different numbers of neutrons. Isotopes of atoms with unstable nuclei are called **radioisotopes.** These unstable nuclei emit radiation to attain more stable atomic configurations in a process called radioactive decay. During radioactive decay, unstable nuclei release energy by emitting radiation. The three most common types of radiation are alpha (α), beta (β), and gamma (γ). **Table 2** summarizes some of their important properties.

Ernest Rutherford (1871–1937), who performed the famous gold foil experiment that helped define modern atomic structure, identified alpha, beta, and gamma radiation when studying the effects of an electric field on the emissions from a radioactive source. The effects of an electric field on gamma rays, alpha particles, and beta particles are shown in **Figure 2.**

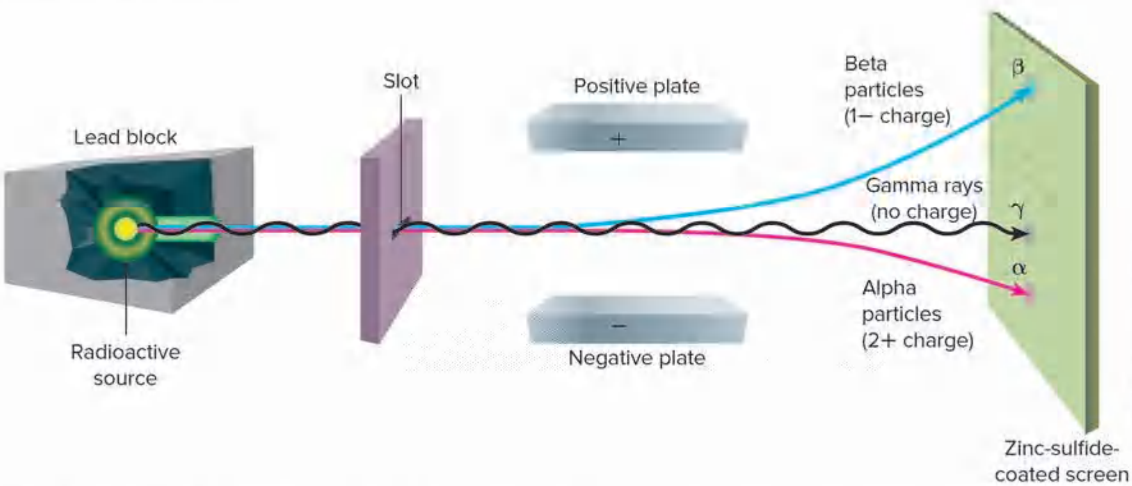


Figure 2 The effect of an electric field depends on the charge and mass of the radiation. Positively charged alpha particles deflect toward the negative plate. Negatively charged beta particles deflect toward the positive plate. The lighter beta particles undergo the larger deflection. Gamma rays have no charge and are not affected by an electric field.

Figure 3 A radium-226 nucleus undergoes alpha decay to form radon-222 and an alpha particle.
Compare *the number of protons and neutrons in radium-226 and radon-222.*

Alpha particles

An alpha particle (α) has the same composition as a helium nucleus—two protons and two neutrons—and is therefore given the symbol $^{4}_{2}He$. The charge of an alpha particle is 2+ due to the presence of the two protons. Alpha radiation consists of a stream of alpha particles. Because of their mass and charge, alpha particles are relatively slow-moving compared with other types of radiation. Thus, alpha particles are not very penetrating—a single sheet of paper stops alpha particles. In **Figure 3,** radium-226, an atom whose nucleus contains 88 protons and 138 neutrons, undergoes alpha decay by emitting an alpha particle. Note that the reaction is balanced. That is, the sum of the mass numbers (superscripts) and the sum of the atomic numbers (subscripts) on each side of the arrow are equal. The total number of neutrons plus protons does not change in the nuclear process. Also note that when a radioactive nucleus emits an alpha particle, the product nucleus has an atomic number that is lower by 2 and a mass number that is lower by 4.

Get It?

Describe what happens to the total number of neutrons plus protons in alpha decay.

Beta particles

A beta particle is a very fast-moving electron that is emitted when a neutron in an unstable nucleus converts into a proton. Beta particles are represented by the symbol β or e−. They have a 1− charge. Their mass is so small compared with the mass of nuclei involved in nuclear reactions that it can be approximated to zero.

Beta radiation consists of a stream of fast-moving electrons. An example of the beta decay process is the decay of iodine-131 into xenon-131 by beta-particle emission, as shown in **Figure 4.** Note that the mass number of the product nucleus is the same as that of the original nucleus (they are both 131), but its atomic number has increased by 1 (54 instead of 53). This change in atomic number occurs because a neutron is converted into a proton, as shown by the following equation.

$$n \rightarrow p + \beta$$

Figure 4 An iodine-131 nucleus undergoes beta decay to form xenon-131 and a beta particle.
Explain *How does beta decay affect the mass number of the decaying nucleus?*

As you might recall, the number of protons in an atom determines its identity. Thus, the formation of an additional proton results in the transformation from iodine-131 to xenon-131. Also, note that the electric charge in the equation above is conserved. The neutron is neutral. The proton has a 1+ charge and the beta particle has a 1− charge. Because beta particles are both lightweight and fast-moving, they have greater penetrating power than alpha particles. A thin sheet of metal foil is required to stop beta particles.

Gamma rays

Gamma rays are photons, which are high-energy (short wavelength) electromagnetic radiation. They are denoted by the symbol γ. Because photons have no mass and no charge, the emission of gamma rays does not change the atomic number or mass number of a nucleus. Gamma rays almost always accompany alpha and beta radiation, as they account for most of the energy loss that occurs as a nucleus decays. For example, gamma rays accompany the alpha-decay reaction of uranium-238.

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He + 2\gamma$$

The 2 in front of the γ symbol indicates that two gamma rays of different frequencies are emitted. Because gamma rays have no effect on mass number or atomic number, it is customary to omit them from nuclear equations.

As you have learned, the discovery of X-rays helped set the stage for the discovery of radioactivity. **X-rays,** like gamma rays, are a form of high-energy electromagnetic radiation. However, X-rays are not produced by radioactive sources and their energy is lower than that of gamma rays. They are emitted when inner electrons are knocked out and electrons from higher energy levels drop down to fill the vacancy. **Figure 5** shows an X-ray image taken in space. It allows astronomers to observe objects not visible in optical images. The presence of X-rays indicates phenomena such as exploding stars or black holes. Hospitals and dentists have machines that produce X-rays when a beam of electrons strikes a metal target. The familiar X-ray images are produced as the beam of X-rays passes easily through soft tissue but is partly blocked by hard tissue, such as bone.

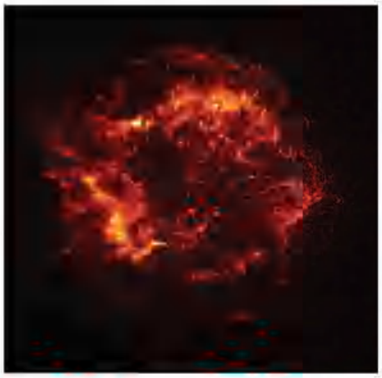


Figure 5 The *Chandra Observatory,* launched in July 1999, photographed X-rays emitted from a cool gas cloud surrounding the black hole at the center of a neighboring galaxy.

Get It?

Compare and contrast X-rays and gamma rays.

WORD ORIGIN

radiation
from the Latin word *radiare*, meaning *to radiate*

CCC CROSSCUTTING CONCEPTS

Energy and Matter In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved. Create a table that shows that the above statement is true. What evidence did you use to make your table?

Penetrating power

The ability of radiation to pass through matter is called **penetrating power.** Alpha particles have a low penetrating power because they move slowly due to their large mass, and their 2+ charge causes them to lose energy quickly through interactions with other particles in matter they encounter. As a result, alpha particles can be stopped by very little shielding. Even a piece of paper, light clothing, or the outer layers of skin will stop them.

The penetrating power of beta particles is higher than alpha particles because beta particles are smaller and faster than alpha particles. However, they still interact with other particles and will be stopped fairly quickly by shielding. For example, metal foil or thick specialized clothing will stop beta particles.

Gamma rays are highly penetrating. Because they have no charge and no mass, gamma rays do not interact much with matter. Therefore, the probability of matter stopping them is low. A thick layer of concrete or lead is relatively effective at shielding against gamma rays, although some gamma radiation may still penetrate.

Penetrating power may be quantified as the depth of water that stops 50 percent of the incoming radiation. Water is used for this purpose because living tissue contains a high proportion of water. Measured in this way, the penetrating power is about 0.03 mm for alpha radiation, about 2 mm for beta radiation, and about 10 cm for gamma radiation. In the case of gamma radiation, for example, this means that a 10 cm layer of water will stop 50 percent of incoming gamma radiation.

Get It?

Explain why the penetrating power of gamma rays is greater than the penetrating power of alpha or beta particles.

Check Your Progress

Summary

- Wilhelm Roentgen discovered X-rays in 1895.
- Henri Becquerel, Marie Curie, and Pierre Curie pioneered the fields of radioactivity and nuclear chemistry.
- Radioisotopes emit radiation to attain more stable atomic configurations.

Demonstrate Understanding

1. **List** the different types of radiation and their charges.
2. **Compare** the subatomic particles involved in nuclear and chemical reactions.
3. **Explain** how you know whether the reaction is chemical or nuclear when an atom undergoes a reaction and attains a more stable form.
4. **Calculate** The approximate energy values in **Table 2** are given in units of MeV. Convert each value into Joules using the following conversion factor: $1\ \text{MeV} = 1.6 \times 10^{-13}\ \text{J}$.
5. **Summarize** Make a time line that summarizes the major events that led to the understanding of alpha, beta, and gamma radiation.

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LESSON 2
RADIOACTIVE DECAY

FOCUS QUESTION

Why are some nuclei radioactive?

Nuclear Stability

Except for the emission of gamma radiation, radioactive decay involves the conversion of an element into another element. Such a reaction, in which an atom's atomic number is altered, is called **transmutation.** Whether an atom spontaneously decays and what type of radiation it emits depends on its neutron-to-proton ratio.

The protons and neutrons in an atom's nucleus are referred to as **nucleons.** Despite the strong electrostatic repulsion forces among protons, all nucleons remain bound in the dense nucleus because of the **strong nuclear force.** As shown in **Figure 6,** the strong nuclear force acts on subatomic particles that are extremely close together and overcomes the electrostatic repulsion among protons. Nuclear stability is related to the balance between electrostatic and strong nuclear forces.

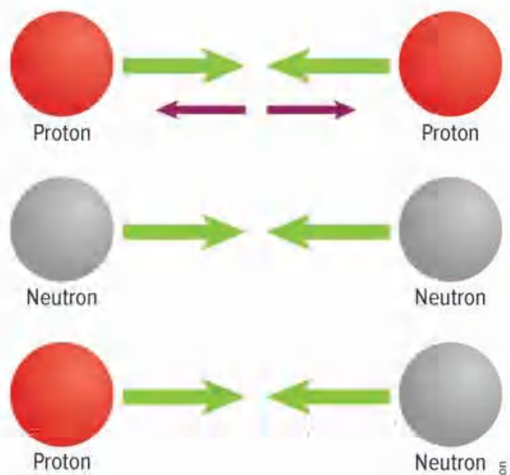


Figure 6 A repulsive electrostatic force, represented by the purple arrows, acts between the two positively charged protons. The strong nuclear force, represented by the green arrows, acts between any two or more nucleons and is always attractive. Because neutrons do not repel one another or protons, experiencing only the attractive strong force, their presence adds to the overall attraction among nucleons.

Infer *What is the effect of the electrostatic force between two neutrons? Between a proton and a neutron?*

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Laboratory: Modeling Isotopes

Construct an explanation to determine the stability and change of an atom experiencing spontaneous radioactive decay.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Neutron-to-proton ratio

To a certain degree, the stability of a nucleus can be correlated to its neutron-to-proton (n/p) ratio. For atoms with low atomic numbers (<20), the most stable nuclei are those with neutron-to-proton ratios of 1:1. For example, helium ($^{4}_{2}$He.) has two neutrons and two protons, and a neutron-to-proton ratio of 1:1. As atomic number increases, more and more neutrons are needed to produce a strong nuclear force that is sufficient to balance the electrostatic repulsion force between protons. Therefore, the neutron-to-proton ratio for stable atoms gradually increases, reaching a maximum of approximately 1.5:1 for the largest atoms. An example of this is lead ($^{206}_{82}$Pb). With 124 neutrons and 82 protons, lead has a neutron-to-proton ratio of 1.51:1.

Get It?

Explain why the neutron-to-proton ratio of stable nuclei increases as the atomic number increases.

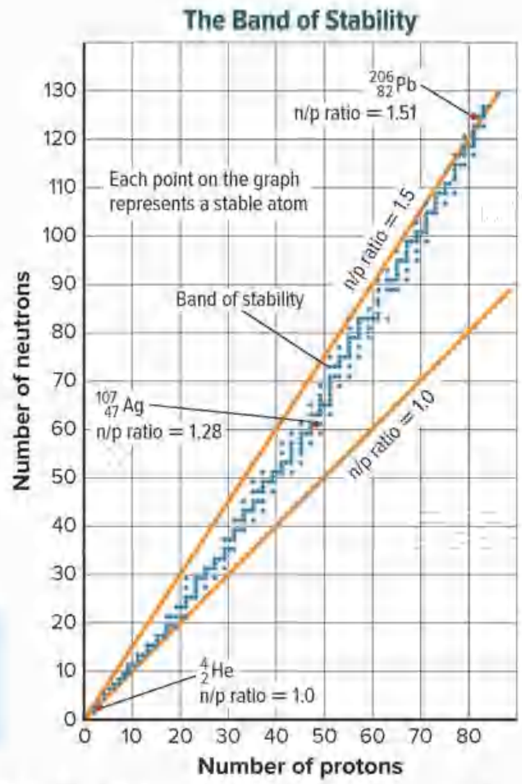


Figure 7 The band of stability is the region where all stable nuclei fall when plotting the number of neutrons versus the number of protons. As the atomic number increases, the neutron-to-proton ratio (n/p) increases from 1:1 to 1.5:1.

The band of stability

Examine the plot of the number of neutrons versus the number of protons for all known stable nuclei shown in **Figure 7.** Notice that the slope of the plot indicates that the number of neutrons required for a nucleus to be stable increases as the number of protons increases. This correlates with the increase in the neutron-to-proton ratio of stable nuclei with increasing atomic number. The area on the graph within which all stable nuclei are found is known as the **band of stability.**

As shown in **Figure 7,** $^{4}_{2}$He and $^{206}_{82}$Pb are both positioned within the band of stability although they have a different neutron-to-proton ratio. All nuclei outside the band of stability—either above or below—are radioactive and undergo decay in order to gain stability. After decay, the new atom is positioned more closely to, if not within, the band of stability. The band of stability ends at lead-208; all elements with atomic numbers greater than 82 are radioactive.

Analysis of the types of decay that various unstable nuclei undergo reveals a pattern. Unstable nuclei found above the band of stability undergo beta decay, which decreases the neutron-to-proton ratio. Nuclei found under the band of stability undergo other types of decay that result in an increase of their neutron-to-proton ratio. Heavy nuclei beyond the band undergo alpha decay.

Get It?

Define the band of stability and relate it to the value of the neutron-to-proton ratio.

Types of Radioactive Decay

The type of radioactive decay a particular radioisotope undergoes depends to a large degree on the underlying causes for its instability. Atoms lying above the band of stability generally have too many neutrons to be stable, whereas atoms lying below the band of stability tend to have too many protons to be stable. Depending on the relative number of neutrons and protons, atoms can undergo different types of decay—beta decay, alpha decay, positron emission, or electron capture—to gain stability.

Beta decay

A radioisotope that lies above the band of stability is unstable because it has too many neutrons relative to its number of protons. For example, unstable $^{14}_{6}C$ has a neutron-to-proton ratio of 1.33:1, whereas stable elements of similar mass, such as $^{12}_{6}C$ and $^{14}_{7}N$, have neutron-to-proton ratios of approximately 1:1. It is not surprising, then, that $^{14}_{6}C$ undergoes beta decay, as this type of decay decreases the number of neutrons in the nucleus.

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + \beta$$

Figure 8a shows the beta decay of carbon-14 into nitrogen-14. Note that the atomic number of the product nucleus, $^{14}_{7}N$, has increased by one. The nitrogen-14 atom now has a stable neutron-to-proton ratio of 1:1. Thus, beta emission has the effect of increasing the stability of a neutron-rich atom by increasing its atomic number, that is, by lowering its neutron-to-proton ratio. The resulting atom is closer to, if not within, the band of stability.

Get It?

Explain why radioisotopes above the band of stability are unstable.

Figure 8 Depending on where nuclei lie on the band of stability, they can emit a beta particle or an alpha particle.

Compare and contrast *beta decay and alpha decay in terms of the atomic number of the nuclei involved in the reaction.*

SCIENCE USAGE v. COMMON USAGE

unstable

Science usage: spontaneously radioactive

Unstable atoms decay to reach a more stable state.

Common usage: not firm or fixed in one place

The chair is unstable because one of its legs is shorter than the others.

Alpha decay

All nuclei with more than 82 protons are radioactive and decay spontaneously. Both the number of neutrons and the number of protons must be reduced in order to make these radioisotopes stable. These very heavy nuclei often decay by emitting alpha particles. For example, polonium-210 spontaneously decays into lead-206 by emitting an alpha particle.

$$^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$$

Figure 8b on the previous page shows the alpha decay of polonium-210 into lead-206. The atomic number of $^{210}_{84}\mathrm{Po}$ decreases by 2 and the mass number decreases by 4 as the nucleus decays into $^{206}_{82}\mathrm{Pb}$.

Get It?
Calculate how the neutron-to-proton ratio changes when polonium-210 decays into lead-206.

Positron emission and electron capture

For nuclei with low neutron-to-proton ratios, two common radioactive decay processes occur: positron emission and electron capture. These two processes tend to increase the neutron-to-proton ratio of the neutron-poor atom, bringing the atom closer to, if not within, the band of stability.

Positron emission is a radioactive decay process that involves the emission of a positron from a nucleus. A **positron** is a particle with the same mass as an electron but opposite charge; thus, it is represented by the symbol β^+ or e^+. During positron emission, a proton in the nucleus is converted into a neutron and a positron, and then the positron is emitted.

$$p \rightarrow n + e^+$$

Figure 9a shows the positron emission of a carbon-11 nucleus. Carbon-11 lies below the band of stability and has a low neutron-to-proton ratio of approximately 0.8:1. Carbon-11 undergoes positron emission to form boron-11. Positron emission decreases the number of protons from six to five, and increases the number of neutrons from five to six. The resulting atom, $^{11}_{5}\mathrm{B}$, has a neutron-to-proton ratio of 1.2:1, which is within the band of stability.

Get It?
Explain how positron emission increases the stability of nuclei with low neutron-to-proton ratios.

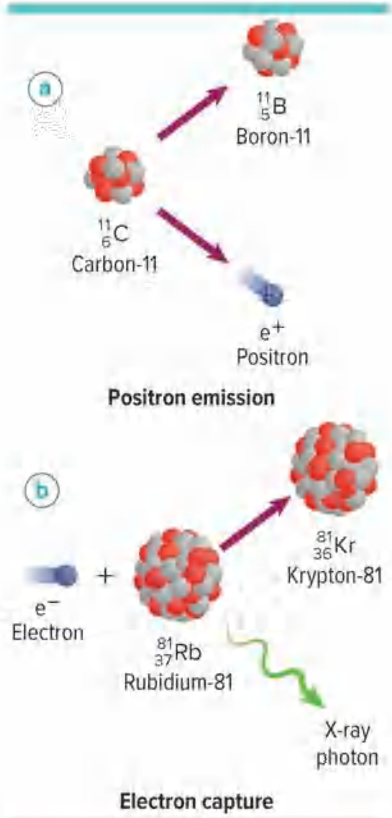


Figure 9 When a nucleus undergoes positron emission or captures an electron, the number of protons decreases by one.
Compare and contrast *how the number of protons and neutrons change during positron emission and electron capture.*

Table 3 **Summary of Radioactive Decay Processes**

Type of Radioactive Decay	Particle Emitted	Change in Mass Number	Change in Atomic Number
Alpha decay	$^{4}_{2}He$	decreases by 4	decreases by 2
Beta decay	β or e^-	no change	increases by 1
Positron emission	β^+ or e^+	no change	decreases by 1
Electron capture	X-ray photon	no change	decreases by 1
Gamma emission	γ	no change	no change

Electron capture is the other common radioactive-decay process that decreases the number of protons in unstable nuclei lying below the band of stability. **Electron capture** occurs when the nucleus of an atom draws in a surrounding electron, usually one from the lowest energy level. This captured electron combines with a proton to form a neutron.

$$p + e^- \rightarrow n$$

The atomic number of the nucleus decreases by 1 as a consequence of electron capture. The formation of the neutron also results in an X-ray photon being emitted. These two characteristics of electron capture are shown in the electron capture of rubidium-81 in **Figure 9b.** The balanced nuclear equation for the reaction is shown below.

$$e^- + {}^{81}_{37}Rb \rightarrow {}^{81}_{36}Kr + \text{X-ray photon}$$

The five types of radioactive decay you have read about in this chapter are summarized in **Table 3.**

Get It?

List the decay processes that result in an increased neutron-to-proton ratio, and those that result in a decreased neutron-to-proton ratio.

Writing and Balancing Nuclear Equations

The radioactive decay processes you have just read about are all examples of nuclear reactions. Nuclear reactions are expressed by balanced nuclear equations just as chemical reactions are expressed by balanced chemical equations. However, in balanced chemical equations, numbers and types of atoms are conserved; in balanced nuclear equations, mass numbers and charges are conserved.

In balancing nuclear equations, you will compare the mass numbers of the product and reactant particles involved in the nuclear reaction to ensure that they are conserved. You will use atomic numbers and the charges of electrons and other charged particles to ensure that charges are conserved. In many cases, your challenge in analyzing nuclear equations will be to determine the identity of an unknown product or reactant.

EXAMPLE Problem 1

BALANCING A NUCLEAR EQUATION NASA uses the alpha decay of plutonium-238 ($^{238}_{94}Pu$) as a heat source on spacecraft. Write a balanced equation for this decay.

1 ANALYZE THE PROBLEM

You are given that a plutonium atom undergoes alpha decay and forms an unknown product. Plutonium-238 is the initial reactant, while the alpha particle is one of the products of the reaction. The reaction is summarized below.

$$^{238}_{94}\text{Pu} \rightarrow {}^{A}_{Z}X + {}^{4}_{2}\text{He}$$

You must determine the unknown product of the reaction, X.

Known	Unknown
reactant: plutonium-238 ($^{238}_{94}Pu$)	mass number of the product $A = ?$
decay type: alpha particle emission ($^{4}_{2}He$)	atomic number of the product $Z = ?$
	reaction product $X = ?$

2 SOLVE FOR THE UNKNOWN

$238 = A + 4$ — Apply the conservation of mass number.

$A = 238 - 4 = 234$ — Solve for A.

Thus, the mass number of X is **234.**

$94 = Z + 2$ — Apply the conservation of charges.

$Z = 94 - 2 = 92$ — Solve for Z.

Thus, the atomic number of X is **92.**

The periodic table identifies the element as uranium (U).

$^{238}_{94}\text{Pu} \rightarrow {}^{234}_{92}\text{U} + {}^{4}_{2}\text{He}$ — Write the balanced nuclear equation.

3 EVALUATE THE ANSWER

The correct formula for an alpha particle is used. The sums of the superscripts and subscripts on each side of the equation are equal. Therefore, the charge and the mass number are conserved. The nuclear equation is balanced.

PRACTICE Problems ADDITIONAL PRACTICE

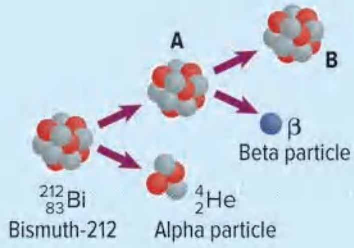
6. Write a balanced nuclear equation for the reaction in which oxygen-15 undergoes positron emission.

7. Thorium-229 is used to increase the lifetime of fluorescent bulbs. What type of decay occurs when thorium-229 decays to form radium-225?

8. CHALLENGE The figure at right shows one way that bismuth-212 can decay, producing isotopes A and B.

a. Write balanced nuclear equations for this decay.

b. Identify the isotopes A and B that are produced.



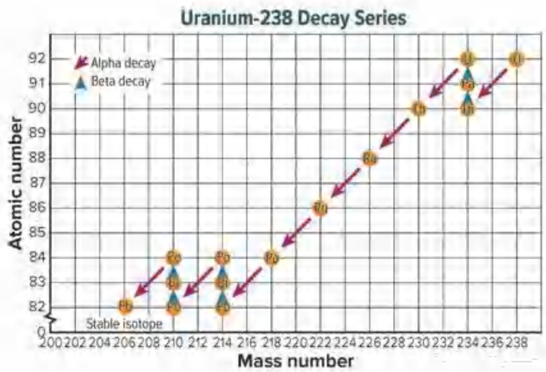


Figure 10 Uranium-238 undergoes 14 different radioactive decay steps before forming stable lead-206.

Radioactive Series

A **radioactive decay series** is a series of nuclear reactions that begins with an unstable nucleus and results in the formation of a stable nucleus. As **Figure 10** shows, uranium-238 first decays to thorium-234, which in turn decays to protactinium-234. Decay reactions continue until a stable nucleus, lead-206, is formed.

Get It?

List each step in the decay of uranium-238. Include the type of decay and the resulting product.

Radioactive Decay Rates

You might wonder how there could be any naturally occurring radioisotopes found on Earth. After all, if radioisotopes undergo continuous radioactive decay, won't they eventually disappear? Furthermore, radioisotopes have been decaying for about 4.6 billion years—the span of Earth's existence. Yet, naturally occurring radioisotopes are not uncommon on Earth. Some radioisotopes, such as carbon-14, are continuously formed in the upper atmosphere of Earth. Others are formed in the universe, during stellar nucleosynthesis for instance. Radioisotopes can also be synthesized in laboratories. The differing decay rates of isotopes also contribute to their presence on Earth.

Radioactive decay rates are measured in half-lives. A **half-life** is the time required for one-half of a radioisotope's nuclei to decay into its products. For example, the half-life of the radioisotope strontium-90 is 29 years. If you had 10.0 g of strontium-90 today, 29 years from now you would have 5.0 g left. **Table 4** on the next page shows how this decay continues through four half-lives of strontium-90. **Figure 11** on the next page presents the data from the table in terms of the percent of strontium-90 remaining after each half-life. The decay continues until a negligible amount of strontium-90 remains.

Get It?

Define the term *half-life*.

Table 4 **The Decay of Strontium-90**

Number of Half-Lives	Elapsed Time	Amount of Strontium-90 Present
0	0 y	10.0g
1	29 y	$10.0\text{ g} \times \left(\frac{1}{2}\right) = 5.00\text{ g}$
2	58 y	$10.0\text{ g} \times \left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 2.50\text{ g}$
3	87 y	$10.0\text{ g} \times \left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 1.25\text{ g}$
4	116 y	$10.0\text{ g} \times \left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 0.625\text{ g}$

The data in **Table 4** can be summarized in a simple equation representing the decay of any radioactive element.

Remaining Amount of Radioactive Element

$$N = N_0\left(\frac{1}{2}\right)^n$$

N is the remaining amount.
N_0 is the inital amount.
n is the number of half-lives that have passed.

The amount remaining is equal to the initial amount times one-half raised the number of half-lives that have passed.

The exponent n can also be replaced with the equivalent quantity t/T, where t is the elapsed time and T is the duration of the half-life. Note that t and T must have the same units of time.

$$N = N_0\left(\frac{1}{2}\right)^{t/T}$$

This type of expression is known as an exponential decay function. **Figure 11** shows the graph of a typical exponential decay function—in this case, the decay curve for strontium-90.

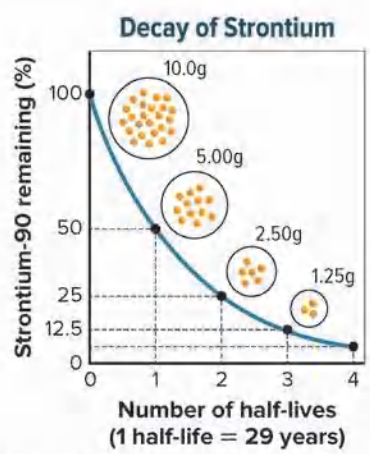


Figure 11 The graph shows how the amount of strontium in a sample changes as a function of the number of half-lives.

Get It?
Infer how much strontium remains after 1.5 half-lives.

Characteristic half-lives

Each radioisotope has its own characteristic half-life. For example, the half-life of polonium-214 is 163.7 μs, the half-life of radon-222 is 3.8 days, and the half-life of uranium-238 is 4.46×10^9 years. Notice the large range of values for half-lives, from millionths of a second to billions of years!

EXAMPLE Problem 2

CALCULATING THE AMOUNT OF REMAINING ISOTOPE Krypton-85 is used in indicator lights of appliances. The half-life of krypton-85 is 11 y. How much of a 2.000-mg sample remains after 33 y?

1 ANALYZE THE PROBLEM

You are given a known mass of a radioisotope with a known half-life. You must first determine the number of half-lives that passed during the 33-year period. Then, use the exponential decay equation to calculate the amount of the sample remaining.

Known	Unknown
Initial amount = 2.000 mg	Amount remaining = ? mg
Elapsed time (t) = 33 y	
Half-life (T) = 11 y	

2 SOLVE FOR THE UNKNOWN

Number of half-lives (n) $= \frac{\text{elapsed time}(t)}{\text{half-life}(T)}$ — Determine the number of half-lives.

$n = \frac{33\text{ y}}{11\text{ y}} = 3.0$ half-lives — Substitute $t = 33$ y and $T = 11$ y.

Amount remaining = (initial amount) $\left(\frac{1}{2}\right)^n$ — Write the exponential decay equation.

Amount remaining = (2.000 mg) $\left(\frac{1}{2}\right)^{3.0}$ — Substitute initial amount = 2.000 mg and $n = 3.0$.

Amount remaining = (2.000 mg) $\left(\frac{1}{8}\right)$ = **0.2500 mg**

3 EVALUATE THE ANSWER

Three half-lives are equivalent to $\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)$, or $\left(\frac{1}{8}\right)$. The answer (0.25 mg) is equal to $\left(\frac{1}{8}\right)$ of the initial amount. The answer has two significant figures because the number of years has two significant figures.

PRACTICE Problems

ADDITIONAL PRACTICE

9. Bandages can be sterilized by exposure to gamma radiation from cobalt-60, which has a half-life of 5.27 y. How much of a 10.0-mg sample of cobalt-60 is left after one half-life? Two half-lives? Three half-lives?

10. If the passing of five half-lives leaves 25.0 mg of a strontium-90 sample, how much was present in the beginning?

11. **CHALLENGE** The table shows the amounts of radioisotopes in three different samples. To the nearest gram, how much will be in Sample B and Sample C when Sample A has 16.2 g remaining?

Sample	Radioisotope	Half-life	Amount (g)
A	cobalt-60	5.27 y	64.8
B	tritium	12.32 y	58.4
C	strontium-90	28.79 y	37.6

Radiochemical dating

Chemical reaction rates are greatly affected by changes in temperature, pressure, and concentration, and by the presence of a catalyst. In contrast, nuclear reaction rates remain constant regardless of such changes. In fact, the half-life of any particular radioisotope is constant. Because of this, radioisotopes can be used to determine the age of an object. The process of determining the age of an object by measuring the amount of a certain radioisotope remaining in that object is called **radiochemical dating.**

LIFE SCIENCE Connection A type of radiochemical dating known as carbon dating is used to measure the age of artifacts that were once part of a living organism. Carbon dating makes use of the radioactive decay of carbon-14, which is formed by cosmic rays in the upper atmosphere at a fairly constant rate. These carbon-14 atoms become evenly spread throughout Earth's biosphere, where they mix with stable carbon-12 and carbon-13 atoms. Plants use carbon dioxide from the environment, which contains all carbon isotopes, to build more complex molecules through the process of photosynthesis. When animals eat plants, the carbon-14 atoms that were part of the plant become part of the animal. Because organisms are constantly taking in carbon compounds, they contain the same ratio of carbon- 14 to carbon-12 and carbon-13 found in the atmosphere. However, after they die, organisms no longer ingest new carbon compounds, and the carbon-14 they already contain continues to decay. The carbon-14 undergoes beta decay to form nitrogen-14.

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \beta$$

Carbon-14 has a half-life of 5730 years. Because the amount of stable carbon in the dead organism remains constant while the carbon-14 continues to decay, the ratio of unstable carbon-14 to stable carbon-12 and carbon-13 decreases. By measuring this ratio and comparing it to the nearly constant ratio present in the atmosphere, the age of an object can be estimated. For example, if an object's C-14 to (C-12 + C-13) ratio is one-quarter of the ratio measured in the atmosphere, the object is approximately two half-lives, or 11,460 years old. Carbon-14 dating is limited to accurately dating objects up to approximately 45,000 years of age. This method was used to date the Great Pyramid of Giza, shown in **Figure 12.**

Figure 12 Using the radiocarbon dating method on organic materials, such as ash and charcoal found at the Great Pyramid of Giza, scientists estimate the pyramid to be more than 4000 years old.

EARTH SCIENCE Connection The decay process of a different radioisotope, uranium-238 to lead-206, is commonly used to date objects such as rocks. Because the half-life of uranium-238 is 4.5×10^9 years, it can be used to estimate the age of objects that are too old to be dated using carbon-14. By radiochemical dating of meteorites, the age of the solar system has been estimated at 4.6×10^9 years. Certain minerals in rocks are more suitable than others for radiochemical dating by this method. The most commonly analyzed mineral is zircon, containing zirconium, silicon, and oxygen. Zircon is suitable for analysis using the decay of uranium-238 to lead-206 because uranium is naturally incorporated into its crystal structure, whereas lead is not. Therefore, any lead found in zircon can be assumed to be there as a result of the decay of uranium-238.

Check Your Progress

Summary

- The conversion of an atom of one element to an atom of another by radioactive decay processes is called *transmutation*.
- Atomic number and mass number are conserved in nuclear reactions.
- A half-life is the time required for half of the atoms in a radioactive sample to decay.
- Radiochemical dating is a technique for determining the age of an object by measuring the amount of certain radioisotopes remaining in the object.

Demonstrate Understanding

12. **Describe** what happens to unstable nuclei.
13. **Explain** how you can predict whether or not an isotope is likely to be stable if you know its number of neutrons and protons.
14. **Describe** the forces acting on the particles within a nucleus and explain why neutrons are the glue holding the nucleus together.
15. **Predict** the nuclear equation for the alpha decay of radium-226 used on the tips of older lightning rods.
16. **Calculate** how much of a 10.0-g sample of americium-241 remains after four half-lives. Americium-241 is a radioisotope commonly used in smoke detectors and has a half-life of 430 y.
17. **Calculate** After 2.00 y, 1.986 g of a radioisotope remains from a sample that had an original mass of 2.000 g.
    a. Calculate the half-life.
    b. How much of the radioisotope remains after 10.00 y?
18. **Graph** A sample of polonium-214 originally has a mass of 1.0 g. Express the mass remaining as a percent of the original sample after a period of one, two, and three half-lives. Graph the percent remaining versus the number of half-lives. Approximately how much time has elapsed when 20% of the original sample remains? The half-life of polonium-214 is 163.7 µs.

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LESSON 3
NUCLEAR REACTIONS

FOCUS QUESTION

What is the relationship between mass and energy and why is it important?

Induced Transmutation

All nuclear reactions, or transmutations, that have been described thus far are examples of radioactive decay, where one element is converted into another element by the spontaneous emission of radiation. However, transmutations can also be forced, or induced, by bombarding a stable nucleus with a neutron or with high-energy alpha, beta, or gamma radiation. In 1919, Ernest Rutherford performed the first laboratory conversion of one element into another element. By bombarding nitrogen-14 with high-speed alpha particles, oxygen-17 and hydrogen-1 were formed. This transmutation reaction is illustrated in **Figure 13** and the reaction is shown below.

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

As Rutherford demonstrated, nuclear reactions can be induced, in other words, produced artificially. The process, which involves striking nuclei with high-velocity particles, is called **induced transmutation.** In the case of charged particles, such as the alpha particles used by Rutherford, the incident particles must be moving at extremely high speeds to overcome the electrostatic repulsion between themselves and the target nucleus. Because of this, scientists have developed methods to accelerate charged particles to extreme speeds by using very strong electrostatic fields and magnetic fields. Particle accelerators are machines built to produce the high-speed particles needed to induce transmutation. Since Rutherford's first experiments involving induced transmutation, scientists have used the technique to synthesize hundreds of new isotopes in the laboratory.

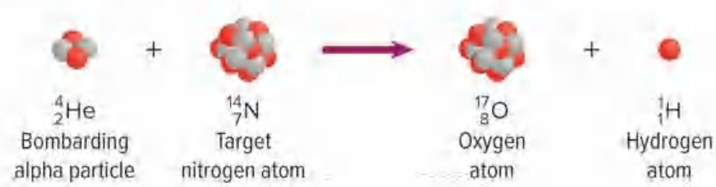


Figure 13 When an alpha particle bombards a nitrogen-14 atom, an atom of oxygen-17 and an atom of hydrogen-1 are produced.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practice: Modeling Fission, Fusion, and Radioactive Decay

HS-PS1-8. Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the process of fission, fusion, and radioactive decay.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the module question?

Transuranium elements

The elements immediately following uranium in the periodic table—elements with atomic numbers 93 and greater—are known as the **transuranium elements.** All transuranium elements have been produced in the laboratory by induced transmutation and are radioactive. Many transuranium elements have been named in honor of their discoverers or the laboratories at which they were created. For example, element 117, tennessine, was so named because some of the key work leading to its discovery was carried out in Tennessee. Scientists continue their ongoing efforts to synthesize new transuranium elements and study their properties.

EXAMPLE Problem 3

INDUCED TRANSMUTATION REACTION EQUATIONS Write a balanced nuclear equation for the induced transmutation of oxygen-16 into nitrogen-13 by proton bombardment. An alpha particle is emitted in the reaction.

1 ANALYZE THE PROBLEM

You are given all of the particles involved in an induced transmutation reaction. Because the proton bombards the oxygen atom, they are reactants and must appear on the reactant side of the reaction arrow.

Known
reactants: oxygen-16 and a proton
products: nitrogen-13 and an α-particle

Unknown
nuclear equation for the reaction = ?

2 SOLVE FOR THE UNKNOWN

Nuclear formula for oxygen-16: $^{16}_{8}O$ — Use the periodic table to obtain the atomic number of oxygen.

Nuclear formula for nitrogen-13: $^{13}_{7}N$ — Use the periodic table to obtain the atomic number of nitrogen.

Nuclear formula for proton: p

Nuclear formula for alpha particle: $^{4}_{2}He$

$^{16}_{8}O + p \rightarrow ^{13}_{7}N + ^{4}_{2}He$ — Write the balanced nuclear equation.

3 EVALUATE THE ANSWER

A proton has a charge of 1+ and a mass number of 1. Therefore, both charge and mass number are conserved. The formula for each participant in the reaction is also correct. The nuclear equation is written correctly.

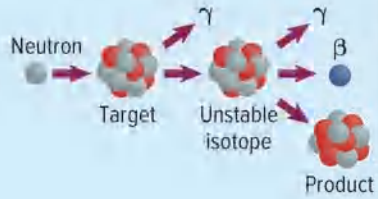
PRACTICE Problems

ADDITIONAL PRACTICE

19. Write the balanced nuclear equation for the induced transmutation of aluminum-27 into sodium-24 by neutron bombardment. An alpha particle is released in the reaction.

20. Write the balanced nuclear equation for the alpha-particle bombardment of $^{239}_{94}Pu$. One of the reaction products is a neutron.

21. CHALLENGE Archeologists sometimes use a procedure called neutron activation analysis to identify elements in artifacts. The figure at right shows one type of reaction that can occur when an artifact is bombarded with neutrons. If the product of the process is cadmium-110, what was the target and unstable isotope? Write balanced nuclear equations for the process to support your answer.



Nuclear Reactions and Energy

In your study of chemical reactions, you read that mass is conserved. For most practical purposes this is true—but, it is not accurate.

Einstein's equation

Albert Einstein's equation relates mass and energy. It states that any reaction produces or consumes energy due to a loss or gain in mass. Energy and mass are equivalent. Note that because c^2 is large, a small change in mass results in a large change in energy.

Energy Equivalent of Mass

$$\Delta E = \Delta mc^2$$

ΔE is the change in energy, in Joules. Δm is the change in mass, in kg. c is the speed of light.

The change in energy is equal to the change in mass times the square of the speed of light.

Mass defect and binding energy

Scientists have determined that the mass of the nucleus is always less than the sum of the masses of the individual protons and neutrons that make up the nucleus. This observed difference in mass between a nucleus and its component nucleons is called the **mass defect.**

When nucleons combine together to form an atom, the energy corresponding to the mass defect is released. Conversely, energy is needed to break apart a nucleus into its component nucleons. The nuclear binding energy can be defined as the amount of energy needed to break one mole of nuclei into its individual nucleons. The larger the binding energy per nucleon, the more strongly the nucleons are held together, and the more stable the nucleus is. Less-stable atoms have lower binding energies per nucleon. In other words, it is harder to break apart a nucleus with a high binding energy than it is to break apart a nucleus with a low binding energy.

Figure 14 shows the average binding energy per nucleon versus the mass number. Note that the binding energy per nucleon reaches a maximum around a mass number of 60. Elements with a mass number near 60 are the most stable.

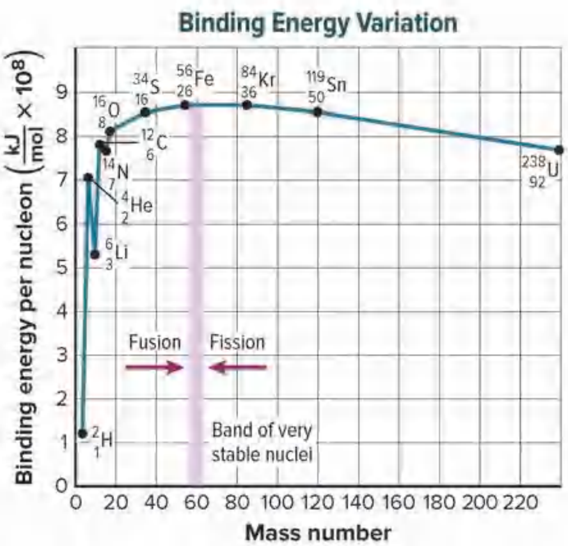


Figure 14 The binding energy per nucleon is a function of the mass number. Light nuclei gain stability by undergoing nuclear fusion. Heavy nuclei gain stability by undergoing nuclear fission.

Get It?

Describe how the binding energy varies as a function of the mass number.

PROBLEM-SOLVING STRATEGY

Calculating Mass Defect

You can calculate the mass defect of an isotope if you know the mass of the isotope and the number and masses of its components. Applying the equation $\Delta E = \Delta mc^2$, you can then derive the equivalent binding energy.

Mass defect $= m_{nucleus} - [N_p m_p + N_n m_n]$

where $m_{nucleus}$ is the mass of the nucleus, m_p is the mass of a proton, m_n is the mass of a neutron, N_p is the number of protons, and N_n is the number of neutrons.

If you start with the mass of the atom, you have to take into account the mass of the electrons. To do so, the mass of a hydrogen atom, which is composed of a proton and an electron, is used instead of the mass of a proton. The equation is then:

Mass defect $= m_{isotope} - [N_p m_H - N_n m_n]$

Use the following values for the calculations: $m_H = 1.007825$ amu and $m_n = 1.008665$ amu. The accepted value for c is 3.00×10^8 m/s.

To calculate the energy in Joules, you can convert the masses into kilograms using 1 amu $= 1.660540 \times 10^{-27}$ kg.

Apply the Strategy

Calculate the mass defect and binding energy of lithium-7. The mass of lithium-7 is 7.016003 amu.

In typical chemical reactions, the energy produced or consumed is so small that the accompanying changes in mass are negligible. In contrast, the mass changes and associated energy changes in nuclear reactions are significant. For example, the energy released from the nuclear reaction of 1 kg of uranium is equivalent to the energy released during the chemical combustion of about four billion kilograms of coal.

Nuclear Fission

The binding energies shown in **Figure 14** on the previous page indicate that heavy nuclei tend to be unstable. To gain stability, they can fragment into several smaller nuclei. Because atoms with mass numbers around 60 are the most stable, heavy atoms (those with mass numbers greater than 60) tend to fragment into smaller atoms in order to increase their stability. The splitting of a nucleus into fragments is known as **nuclear fission.** The fission of a nucleus is accompanied by a very large release of energy. Nuclear power plants use the large release of energy associated with nuclear fission to generate power. The generation of nuclear power is an example of a series of energy transformations in which nuclear energy is transformed into thermal energy and then into electrical energy.

ACADEMIC VOCABULARY

generate
to bring into existence, to originate by a physical or chemical process
Fire generates a lot of heat.

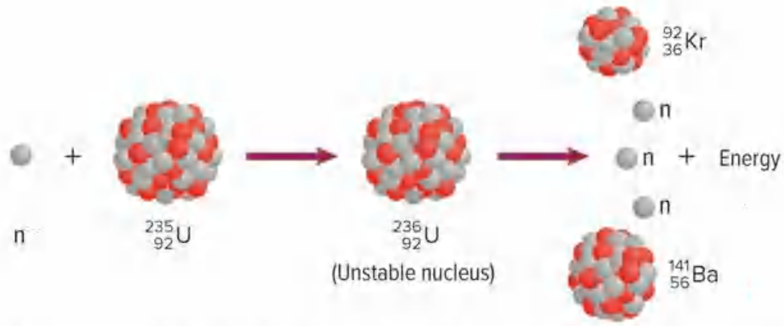


Figure 15 When bombarded with a neutron, uranium-235 forms unstable uranium-236, which then splits into two lighter nuclei and additional neutrons. The fission of uranium-235 is accompanied by a large release of energy.

The first nuclear fission reaction discovered involved uranium-235. As you can see in **Figure 15,** when a neutron strikes a uranium-235 nucleus, it undergoes fission. Barium-141 and krypton-92 are just two of the many possible products of this fission reaction. In fact, scientists have identified more than 200 different product isotopes from the fission of a uranium-235 nucleus.

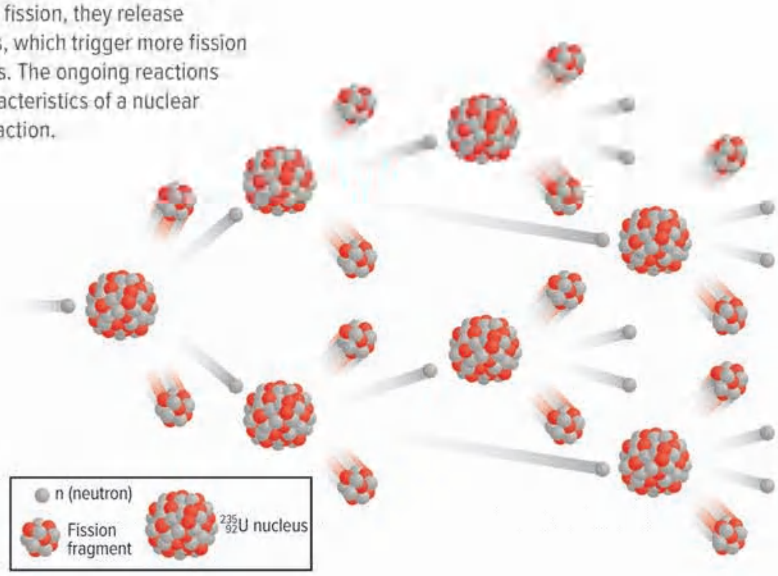
Get It?

Explain why heavy atoms undergo nuclear fission.

Chain reactions

Each fission of uranium-235 releases additional neutrons, as shown in **Figure 15.** If one fission reaction produces two neutrons, these two neutrons can cause two additional fissions. If those two fissions release four neutrons, those four neutrons could then produce four more fissions, and so on, as shown in **Figure 16.** This self-sustaining process in which one reaction initiates the next is called a chain reaction. As you might imagine, the number of fissions and the amount of energy released can increase rapidly. The explosion from an atomic bomb is an example of an uncontrolled chain reaction.

Figure 16 When uranium nuclei undergo fission, they release neutrons, which trigger more fission reactions. The ongoing reactions are characteristics of a nuclear chain reaction.



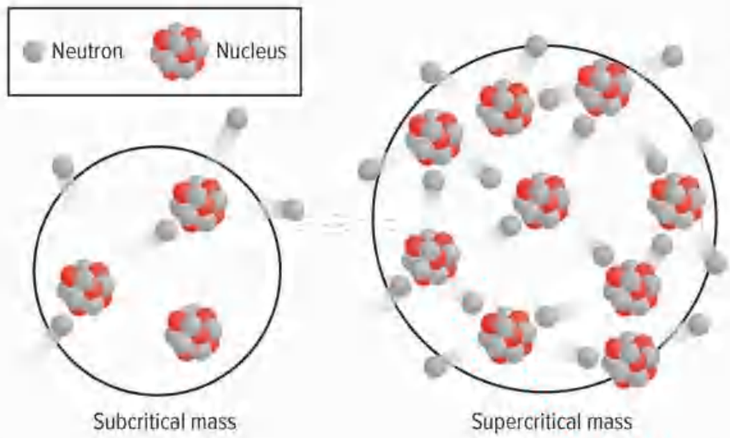


Figure 17 Whether a nuclear reaction can be sustained depends on the amount of matter present. In a subcritical mass, the chain reaction does not start because neutrons escape before causing enough fission to sustain the chain reaction. In a supercritical mass, neutrons cause more and more fissions, and the chain reaction accelerates.

A sample of fissionable material must have sufficient mass in order for a chain reaction to occur. If it does not, neutrons escape from the sample before they can start the chain reaction by striking other nuclei. A sample that is not massive enough to sustain a chain reaction is said to have subcritical mass. A sample that is massive enough to sustain a chain reaction has **critical mass.** When a critical mass is present, the neutrons released in one fission cause other fissions to occur. If much more mass than the critical mass is present, the chain reaction rapidly escalates. This can lead to a violent nuclear explosion. A sample of fissionable material with a mass greater than the critical mass is said to have supercritical mass. **Figure 17** shows the effect of mass on the initiation and progression of a fission reaction.

Nuclear Reactors

Nuclear fission produces the energy generated by nuclear reactors. This energy is primarily used to generate electricity at nuclear power plants, such as the one shown in **Figure 18.** A common fuel is fissionable uranium (IV) oxide (UO_2) encased in corrosion-resistant rods. U-238 is the most abundant isotope (99%) of uranium. U-235, which makes up 0.7% of the natural uranium, has the rare property of being able to undergo induced fission; U-235 atoms undergo fission when hit by a neutron. The fuel used in nuclear power plants is enriched to contain 3% uranium-235, the amount required to sustain a chain reaction, and is called enriched uranium. Additional rods, often made of cadmium or boron, control the fission process inside the reactor by absorbing neutrons released during the reaction.

Keeping the chain reaction going while preventing it from racing out of control requires precise monitoring and continual adjusting of the control rods. Much of the concern about nuclear power plants focuses on the risk of losing control of the nuclear reactor, possibly resulting in the accidental release of harmful levels of radiation. The Three Mile Island accident in the United States in 1979 and the Chernobyl accident in Ukraine in 1986 provide examples of why controlling the reactor is critical. **Figure 19** on the next page shows the city of Pripyat, located 3 km from Chernobyl. The city was completely abandoned after the accident.

Figure 18 The main parts of a nuclear power plant are the reactor under the dome and the cooling tower.

How a nuclear reactor works

The fission within a nuclear reactor is started by a neutron-emitting source and is stopped by positioning the control rods to absorb all of the neutrons produced in the reaction. The reactor core contains a reflector that acts to reflect neutrons back into the core, where they will react with the fuel elements, also called fuel rods. A coolant, usually water, circulates through the reactor core, to carry off the heat generated by the nuclear fission reactions. The hot coolant heats water so that it boils, producing steam that is in turn used to power turbines. The movement of the turbines is used to generate an electric current.

Figure 19 The city of Pripyat was deserted after the accident at the Chernobyl power plant.

Nuclear power plants and fossil-fuel burning power plants are similar. In both types of power plant, heat from a reaction—nuclear fission or chemical combustion of a fossil fuel such as coal—is used to generate steam. The steam then drives turbines that produce electricity, as shown in the nuclear power plant illustrated in **Figure 20.** The other major components of a nuclear power plant are also illustrated in **Figure 20.**

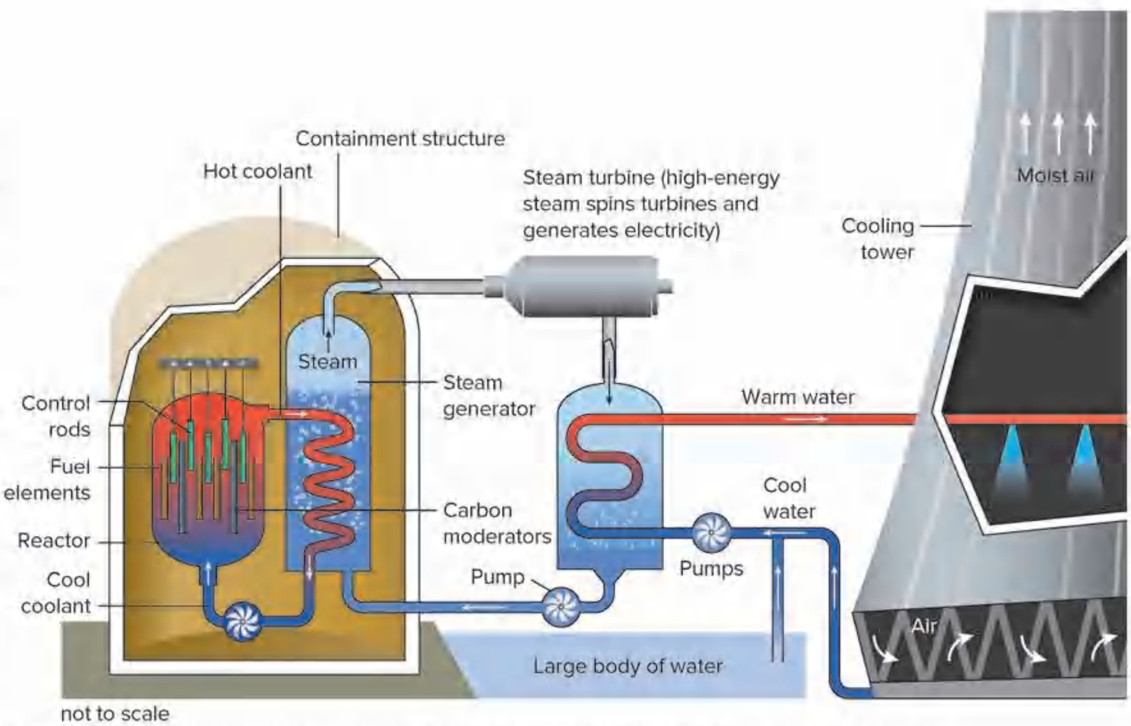


Figure 20 A nuclear reactor produces heat that drives the formation of steam. The energy from the steam spins a turbine, which produces electricity. The steam is eventually cooled and recycled. The water used to cool the steam enters the cooling tower, where steam is released to the atmosphere.

Identify *two examples of energy transformations that take place in a nuclear reactor.*

Figure 21 The interior of a reactor is filled with water. A crane is used to extract and replace fuel rods.

Because of the hazardous radioactive fuels and fission products present at nuclear power plants, a dense concrete structure is usually built to enclose the reactor. The main purpose of the containment structure is to shield personnel and nearby residents from harmful radiation.

As the reactor operates, the fuel rods are gradually depleted and products from the fission reactions accumulate. Because of this, the reactor must be serviced periodically. Spent fuel rods are extracted from the reactor, as shown in **Figure 21,** and can be reprocessed and repackaged to make new fuel rods. Some fission products, however, are extremely radioactive and cannot be used again. These products must be stored as nuclear waste.

Issues associated with nuclear power plants

Risks of accidents, such as the ones mentioned in **Figure 22** on the next page, have to be taken into account when operating nuclear power plants. However, the storage of highly radioactive nuclear waste is still one of the major issues surrounding the debate over the use of nuclear power. Approximately 20 half-lives are required for the radioactivity of nuclear waste materials to reach levels acceptable for biological exposure. For some types of nuclear fuels, the wastes remain substantially radioactive for thousands of years. A considerable amount of scientific research is devoted to the disposal of radioactive wastes. Highly radioactive materials from the reactor core are first treated with advanced technologies that ensure the materials will not deteriorate over a very long period of time. Treated wastes are then stored in sealed containers that are buried deep underground.

Another issue is the limited supply of the uranium-235 used in the fuel rods. One option is to build reactors that produce new quantities of fissionable fuels. Reactors able to produce more fuel than they use are called **breeder reactors.** Although the design of breeder reactors poses many difficult technical problems, they are currently in operation in several countries.

Get It?

Infer how the storage of nuclear wastes affects the environment.

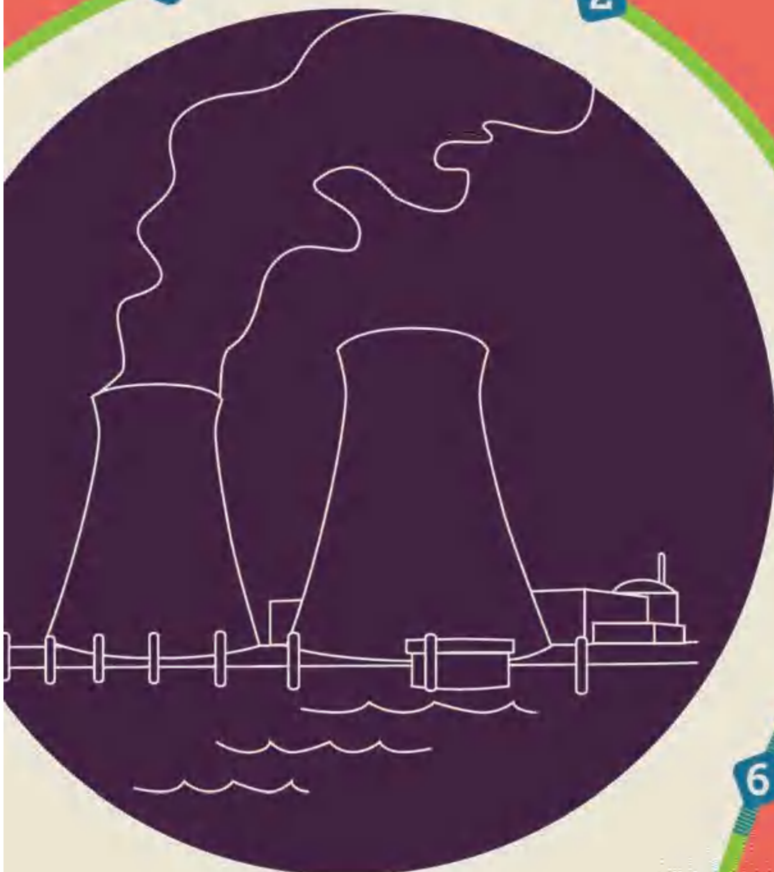


Figure 22

The Nuclear Age

The discovery of X-rays in 1895 initiated a series of breakthroughs in understanding atomic nuclei. Today, nuclear chemistry applications involving medicine, weaponry, and energy affect the lives of people worldwide.

1 **1898** Marie and Pierre Curie discover the radioactive elements polonium and radium. Their work establishes the early framework for the study of nuclear chemistry.

2 **1919** The first artificially induced nuclear reaction transmutes nitrogen into an isotope of oxygen by bombarding nitrogen gas with alpha particles.

3 **1934** Enrico Fermi bombards heavy elements with neutrons. Ida Noddack reviews these experiments and suggests that smaller nuclei might have been produced.

4 **1941–1945** Manhattan Project scientists develop uranium and plutonium bombs, which were dropped on Hiroshima and Nagasaki, Japan, in 1945 and ended World War II.

5 **1949** Radiocarbon dating allows scientists to determine the age of artifacts made from plant-based materials as old as 45,000 years.

6 **1960s** Scientists research using high-energy radiation to treat cancer. Clinical trials bring dramatic improvement in the treatment and cure of malignant tumors.

7 **1979 | 1986** Nuclear power plant accidents at Three Mile Island, Pennsylvania, and Chernobyl, Ukraine, focus world attention on the dangers associated with nuclear power.

8 **2010** Scientists using NASA's Fermi Gamma-ray Space Telescope discover two massive bubbles, one above and one below the core of the Milky Way. They are thought to be the result of activity from either a black hole or star formation.

Nuclear Fusion

Recall from the binding energy diagram in **Figure 14** that a mass number of about 60 has the most stable atomic configuration. Thus, it is possible to bind together two or more light (mass number less than 60) and less-stable nuclei to form a single more-stable nucleus. The combining of atomic nuclei is called **nuclear fusion.** Nuclear fusion reactions, which are responsible for producing the heaviest elements, can release very large amounts of energy. You already have everyday knowledge of this fact—the Sun is powered by a series of fusion reactions as hydrogen atoms fuse to form helium atoms.

$$4\,^{1}_{1}H \rightarrow \,^{4}_{2}He + 2e^{+} + \text{energy}$$

Scientists have spent several decades researching nuclear fusion. It is a promising source of energy and has several advantages compared to nuclear fission. Lightweight isotopes used to fuel the reactions, such as hydrogen, are abundant. Fusion reaction products are not generally radioactive. Nuclear fusion produces large amounts of energy. Fusion reactions produce more energy per unit of mass of fuel than fission reactions. This could solve the problem of many societies' increasing needs for electricity.

Real-World CHEMISTRY

Nuclear Fusion

SOLAR FUSION Nuclear fusion reactions are responsible for the glow and heat from stars such as the Sun. The temperature of the Sun's core is about 15,000,000 K. It is so hot and dense that hydrogen nuclei fuse to produce helium. After billions of years, the Sun's hydrogen will be mostly depleted. Its temperature will rise to about 100,000,000 K, and the fusion process will then change helium into carbon.

Using nuclear fusion for energy

Unfortunately, there are major problems that must be overcome before fusion can be used to produce energy on a commercially viable scale. One such problem is that fusion requires extremely high energies to initiate and sustain a reaction. The required energy, which is achieved only at extremely high temperatures, is needed to overcome the electrostatic repulsion between the nuclei in the reaction. Because of the energy requirements, fusion reactions are also known as **thermonuclear reactions.** A temperature of 5,000,000 K is required to fuse hydrogen atoms. This temperature—and even higher temperatures—have been achieved using an atomic explosion to initiate the fusion process, but this approach is not practical for controlled electric power generation.

Another significant problem is confinement of the reaction. There are currently no materials capable of withstanding the tremendous temperatures that are required by a fusion reaction. Much of the current research centers around an apparatus called a tokamak reactor. The name *tokamak* comes from Russian and means *toroidal chamber with an axial magnetic field.* A tokamak reactor, shown in **Figure 23** on the next page, is a donut-shaped device that uses strong magnetic fields to contain the fusion reaction. While significant progress has been made in the field of fusion, temperatures high enough for continuous fusion have not yet been sustained for long periods of time.

Get It?

Explain the link between the Sun's temperature and the release of such an enormous amount of energy.

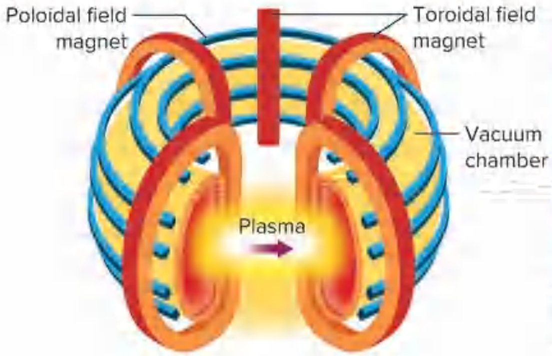


Figure 23 A tokamak reactor, a ring-shaped reactor, uses strong magnetic fields to contain the intensely hot fusion reaction and keep it from direct contact with the reactor interior walls. The poloidal magnets follow the shape of the reactor, and the toroidal magnets wrap around the reactor.

Check Your Progress

Summary

- Induced transmutation is the bombardment of nuclei with particles in order to create new elements.
- In a chain reaction, one reaction induces others to occur. A sufficient mass of fissionable material is necessary to initiate the chain reaction.
- Fission and fusion reactions release large amounts of energy.

Demonstrate Understanding

22. **Explain** why energy is released when nucleons combine to form an atom but is needed to break a nucleus apart.
23. **Compare and contrast** nuclear fission and fusion.
24. **Describe** the process that occurs during a nuclear chain reaction and explain how to monitor a chain reaction in a nuclear reactor.
25. **Explain** how nuclear fission can be used to generate electric power.
26. **Formulate an argument** supporting or opposing nuclear power as your state's primary power source. Assume the primary source of power currently is the burning of fossil fuels.
27. **Calculate** What is the energy change (ΔE) associated with a change in mass (Δm) of 1.00 mg?
28. **Interpret Graphs** Use the graph in **Figure 14** to answer the following questions.
    a. Why is the isotope $^{56}_{26}Fe$ highest on the curve?
    b. Are more stable isotopes located higher or lower on the curve?
    c. Compare the stability of Li-6 and He-4.

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LESSON 4

APPLICATIONS AND EFFECTS OF NUCLEAR REACTIONS

FOCUS QUESTION

What are some applications of nuclear reactions?

Detecting Radioactivity

Radiation energetic enough to ionize matter it contacts is called **ionizing radiation.** The Geiger counter is an ionizing radiation detection device. As shown in **Figure 24,** a Geiger counter consists of a metal tube filled with a gas. In the center of the tube is a wire connected to a power supply. When ionizing radiation penetrates the end of the tube, the gas absorbs the radiation and forms ions and free electrons. The free electrons are attracted to the wire, causing an electric current. A meter measures the current flow through the ionized gas, which indicates the amount of ionizing radiation present.

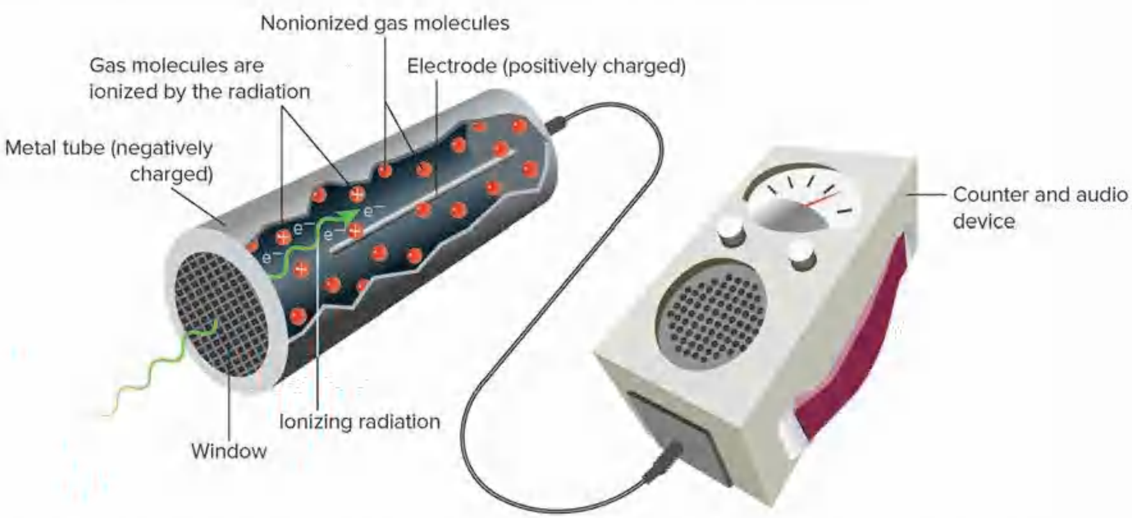

Figure 24 A Geiger counter is used to detect and measure radiation levels. Ionizing radiation produces an electric current in the counter. The current is displayed on a scaled meter, and a speaker produces audible sounds that vary according to the current flow caused by the ionizing radiation.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practice: Human Health and Radiation Frequency

HS-PS4-4. Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

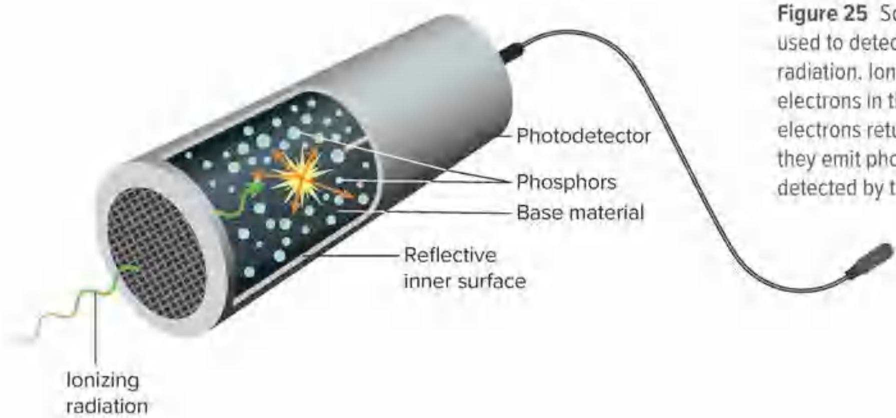

Figure 25 Scintillation counters are used to detect the presence of ionizing radiation. Ionizing radiation excites the electrons in the phosphors. As the electrons return to their ground states, they emit photons, which are then detected by the photodetector.

Monitoring the radiation dose received by people who work near radioactive sources is important to ensure their safety. People who work near radioactive sources might be required to wear a thermoluminescent dosimeter (TLD) badge, which contains a tiny crystal. Radiation excites electrons within the crystal. To determine the radiation dose, the crystal is heated, and the electrons return to their ground states, emitting light. Radioactivity readers detect this light as a measure of the radiation dose to which a worker has been exposed.

Another detection device is a scintillation counter. Scintillations are brief flashes of light produced when ionizing radiation excites the electrons in certain types of atoms or molecules called phosphors. A scintillation counter contains a base material–often a plastic, a crystal, or a liquid–containing phosphors, as shown in **Figure 25.** Ionizing radiation that strikes the scintillation counter can transfer energy either directly to the phosphors or to the base material, which then transfers the energy to the phosphors. This energy excites electrons in the phosphors. As these electrons return to their ground states, they emit light. This light is transmitted through the base material to a photodetector that converts the light to an electrical signal. The number and brightness of the scintillations indicate the amount of ionizing radiation.

Get It?

Summarize how a scintillation counter works.

Uses of Radiation

With proper safety procedures, radiation can be useful in many scientific experiments and industrial applications. For instance, neutron activation analysis is used to detect trace amounts of elements present in a sample. Computer-chip manufacturers use this technique to analyze the composition of highly purified silicon wafers. In the process, the sample is bombarded with a beam of neutrons from a radioactive source, causing some of the atoms in the sample to become radioactive. The type and amount of radiation emitted by the sample is used to determine the types and quantities of elements present. Neutron activation analysis is a highly sensitive measurement technique capable of detecting quantities of less than 1×10^{-9} atoms in a sample. Another application of radiation is the use of beta emission to measure paper thickness.

Using radioisotopes

Radioisotopes can also be used to follow the course of an element through a chemical reaction. For example, CO_2 gas containing radioactive carbon-14 isotopes has been used to study glucose formation in photosynthesis.

$$6CO_2 + 6H_2O \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

Because the CO_2 containing carbon-14 is used to trace the progress of carbon through the reaction, it is referred to as a **radiotracer.** A radiotracer is a radioisotope that emits non-ionizing radiation and is used to signal the presence of an element or specific substance. The fact that all of an element's isotopes have the same chemical properties makes the use of radioisotopes possible. Thus, replacing a stable atom of an element in a reaction with one of its isotopes does not alter the reaction. Radiotracers are important in a number of areas of chemical research, particularly in analyzing the reaction mechanisms of complex, multistep reactions.

Radiotracers also have important uses in medicine. Iodine-131, for example, is commonly used to detect diseases associated with the thyroid gland. If a problem is suspected, the patient will drink a solution containing a small amount of iodine-131. After the iodine is absorbed, the amount of iodine taken up by the thyroid is measured and used to monitor the functioning of the thyroid gland.

Get It?

Define *radiotracer.*

Treating cancer

Radiation can pose serious health problems for humans because it can damage or destroy healthy cells. However, radiation can also destroy unhealthy cells, such as cancer cells. All cancers are characterized by the rapid growth of abnormal cells. This growth can produce masses of abnormal tissue, called malignant tumors. Radiation therapy is used to treat cancer by destroying the cancer cells. In fact, cancer cells are more susceptible to destruction by radiation than healthy ones. **Figure 26** shows an MRI of a malignant tumor in a patient's brain. If all goes well, the tumor will be destroyed. Unfortunately, in the process of destroying unhealthy cells, radiation also destroys some healthy cells. Despite this major drawback, radiation therapy has become one of the most effective treatment options in the fight against cancer.

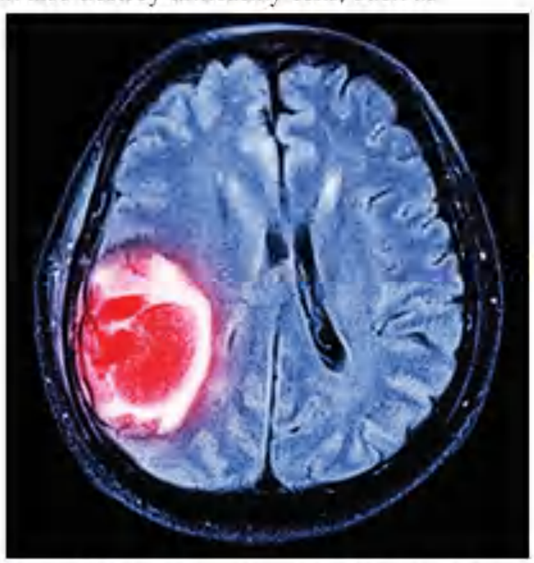

Figure 26 Radiation can be used to treat cancer. This image shows a cancerous tumor in a patient's brain. The tumor is shown in pink.

Figure 27 In PET, gamma rays emitted by the radiotracers absorbed by the patients are measured with a detector such as the one shown on the left. The PET scan on the right shows different areas of the brain emitting gamma rays. These images might help doctors locate a tumor or observe a brain function.

Using positron emission

Another radiation-based medical diagnostic tool is called positron emission transaxial tomography (PET). In this procedure, a radiotracer that decays by positron emission is injected into the patient's bloodstream. Positrons that are emitted by the radiotracer cause gamma-ray emissions. These emissions are then detected by an array of sensors surrounding the patient, as shown in **Figure 27.** PET scans can be used to diagnose diseases or study the parts of the brain that are activated under given circumstances, also shown in **Figure 27.**

Biological Effects of Radiation

Although radiation has a number of medical and scientific applications, it can be very harmful. The damage produced from ionizing radiation absorbed by the body depends on several factors, such as the type of radiation, its energy, the type of tissue absorbing the radiation, the penetrating power, and the distance from the source of the radiation. The skin lesion shown in **Figure 28** is an example of such damage.

Figure 28 Radiation can disrupt cell processes and damage skin.

Infer *Is the lesion pictured here somatic or genetic?*

STEM CAREER Connection

Biomedical Engineer

Biomedical engineers apply engineering skills to medical problems. One of their jobs is to design equipment and software, such as those used in positron emission transaxial tomography, that help treat or diagnose medical conditions. If you'd like to combine a love of technology with a desire to help people, this may be the career for you.

LIFE SCIENCE Connection High-energy ionizing radiation is dangerous because it can fragment and ionize molecules within biological tissue. A free radical is an atom or molecule that contains one or more unpaired electrons and is one example of the highly reactive products of ionizing radiation. In a biological system, free radicals can affect a large number of other molecules and ultimately disrupt the operation of normal cells. Ionizing radiation damage to living systems can be classified as either somatic or genetic. Somatic damage affects only nonreproductive body tissue. It includes burns and cancer caused by damage to the cell's growth mechanism. Genetic damage can affect offspring by damaging reproductive tissue. Such damage is difficult to study because it might not become apparent for several generations.

Dose of radiation

A dose of radiation refers to the amount of radiation a body absorbs from a radioactive source. Two units, the rad and the rem, are commonly used to measure doses. The rad, which stands for radiation-absorbed dose, is a measure of the amount of radiation that results in the absorption of 0.01 J of energy per kilogram of tissue. The dose in rads, however, does not account for the energy of the radiation, the type of living tissue absorbing the radiation, or the time of the exposure. To account for these factors, the dose in rads is multiplied by a numerical factor that is related to the radiation's effect on the tissue involved. The result of this multiplication is a unit called the rem. The rem, which stands for roentgen equivalent for man, is named after Wilhelm Roentgen, who discovered X-rays in 1895. **Table 5** summarizes the short-term effects of radiation on humans, depending on the dose.

Intensity and distance

The intensity of radiation depends on the distance from the source as shown by the equation below. The farther away the source, the lower the intensity. The intensity of radiation is measured in amount of radiation per unit of time and/or surface, such as mrem/s•m^2.

Radiation Intensity and Distance

$$I_1 d_1^2 = I_2 d_2^2$$

d_1 and d_2 are two distances from the source.
I_1 is the intensity at d_1, and I_2 is the intensity at d_2.

The intensity of radiation at a distance d_1 from the source multiplied by the square of the distance equals the intensity of the radiation at a distance d_2 multiplied by the square of the distance.

Table 5 **Effects of Short-term Radiation Exposure**

Dose (rem)	Effects on Humans
0–25	no detectable effects
25–50	temporary decrease in white-blood-cell population
100–200	nausea, substantial decrease in white-blood-cell population
500	50% chance of death within 30 days of exposure

Sources of radiation

A variety of sources constantly bombard your body with radiation. Your exposure to these sources results in an average annual radiation exposure of 100–300 millirems of high-energy radiation or 0.1–0.3 rems. **Table 6** shows your annual exposure to common radiation sources.

Table 6 Average Annual Radiation Exposure

Source	Average Exposure (mrem/y)
Cosmic radiation	20–50
Radiation from the ground	25–175
Radiation from buildings	10–160
Radiation from air	20–260
Human body (internal)	~20
Medical and dental X-rays	50–75
Nuclear weapon testing	<1
Air travel	5
Total average	100–300

Check Your Progress

Summary

- Different types of counters are used to detect and measure radiation.
- Radiotracers are used to diagnose disease and to analyze chemical reactions.
- Short-term and long-term radiation exposure can cause damage to living cells.

Demonstrate Understanding

29. **Explain** one way in which nuclear chemistry is used to diagnose or treat disease.
30. **Describe** several methods used to detect and measure radiation.
31. **Compare and contrast** somatic and genetic biological damage.
32. **Explain** why it is safe to use radioisotopes to diagnose medical problems.
33. **Calculate** A lab worker receives an average radiation dose of 21 mrem each month. Her allowed dose is 5,000 mrem/y. On average, what fraction of her yearly dose does she receive?
34. **Interpret Data** Look at the data in **Table 6.** Suppose someone is exposed to the maximum values listed for average annual radiation from the ground, from buildings, and from the air. What fraction would the person receive of the minimum short-term dose (25 rem) that causes a temporary decrease in white blood cell population?

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STEM AT WORK

Disease Detectives

Nuclear medicine technologists are medical professionals who help doctors diagnose and track patients' diseases and injuries by taking images of the body. Their work employs cutting-edge technology, including gamma cameras and positron emission tomography (PET) scanners. They work in hospitals, doctors' offices, imaging facilities, and diagnostic laboratories.

Nuclear medicine technologists prepare and administer radioactive drugs to patients before diagnostic tests to detect abnormalities in the body.

Radioactive Drugs

Nuclear medicine technologists prepare and administer drugs that contain radioisotopes. Depending on the test, patients can receive an injection, or they can inhale or swallow the drug. These drugs, which belong to a class called *radiopharmaceuticals*, emit radiation and cause parts of the body to show up differently in images taken by gamma cameras and other equipment. Areas with atypical concentrations of radioactivity signal problems. The drugs enable doctors to see parts of the body that are diseased, damaged, or not functioning properly. Tumors are detected in this way.

Nuclear medicine is also used to treat different diseases. Nuclear medicine technologists administer various radiotherapy procedures, such as radiation therapy for breast, prostate, and bone cancers.

Testing Equipment

Nuclear medicine technologists operate specialized equipment and use computers to process the data produced by the tests. In conjunction with images produced by gamma cameras and PET scanners, they may run tests using X-ray radiography, magnetic resonance imaging (MRI) scanners, computed tomography (CT), and computerized axial tomography (CAT) scanners.

Nuclear medicine technologists also work closely with patients, gathering medical information, preparing them for tests, and explaining how the tests work. Thanks to technology and dedicated professionals in nuclear medicine, diseases are detected earlier and lives are saved every day.

ASK QUESTIONS TO CLARIFY

Write several questions that you have about nuclear medicine and nuclear medicine technologists. Use print or online sources to find answers. Share the questions and answers with your classmates.

STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 NUCLEAR RADIATION

- Wilhelm Roentgen discovered X-rays in 1895.
- Henri Becquerel, Marie Curie, and Pierre Curie pioneered the fields of radioactivity and nuclear chemistry.
- Radioisotopes emit radiation to attain more stable atomic configurations.

- radioisotope
- X-ray
- penetrating power

Lesson 2 RADIOACTIVE DECAY

- The conversion of an atom of one element to an atom of another by radioactive decay processes is called *transmutation*.
- Atomic number and mass number are conserved in nuclear reactions.
- A half-life is the time required for half of the atoms in a radioactive sample to decay.

$$N = N_0\left(\frac{1}{2}\right)^n \text{ or } N = N_0\left(\frac{1}{2}\right)^{t/T}$$

- Radiochemical dating is a technique for determining the age of an object by measuring the amount of certain radioisotopes remaining in the object.

- transmutation
- nucleon
- strong nuclear force
- band of stability
- positron emission
- positron
- electron capture
- radioactive decay series
- half-life
- radiochemical dating

Lesson 3 NUCLEAR REACTIONS

- Induced transmutation is the bombardment of nuclei with particles in order to create new elements.
- In a chain reaction, one reaction induces others to occur. A sufficient mass of fissionable material is necessary to initiate the chain reaction.
- Fission and fusion reactions release large amounts of energy.

$$E = mc^2$$

- induced transmutation
- transuranium element
- mass defect
- nuclear fission
- critical mass
- breeder reactor
- nuclear fusion
- thermonuclear reaction

Lesson 4 APPLICATIONS AND EFFECTS OF NUCLEAR REACTIONS

- Different types of counters are used to detect and measure radiation.
- Radiotracers are used to diagnose disease and to analyze chemical reactions.
- Short-term and long-term radiation exposure can cause damage to living cells.

$$I_1d_1^2 = I_2d_2^2$$

- ionizing radiation
- radiotracer

THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

Where does the Sun get all its energy?

CER Claim, Evidence, Reasoning

Explain Your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will apply your evidence from this module and complete your project.

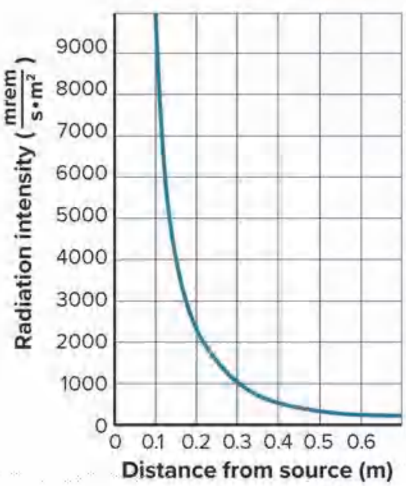
GO FURTHER

SEP Data Analysis Lab

How does distance affect radiation exposure?

When one of the reactors at the Chernobyl nuclear power plant exploded, the radiation spread over thousands of kilometers. The intensity of the radiation decreased with the distance from the reactor.

Data and Observations The graph shows the intensity of a radioactive source versus the distance from the source. The unit of radiation intensity (millirems per second per square meter) indicates the amount of radiation striking a square meter each second.



CER Analyze and Interpret Data

1. **Claim** How does the radiation exposure change as the distance doubles from 0.1 m to 0.2 m? How does it change as the distance quadruples from 0.1 m to 0.4 m?
2. **Evidence, Reasoning** Determine the distance from the source at which the radiation decreased to 0.69 mrem/s•m^2. This intensity is the maximum radiation exposure intensity considered safe. (*Hint: Use the equation* $\frac{I_1}{I_2} = \frac{d_2^{\,2}}{d_1^{\,2}}$.)

Credits