UNIT 7

Changes in Matter

Chapter 19

Molecules and Compounds

Introduction to Chapter 19

Elements are made up of one type of atom. Compounds are made up of molecules which consist of more than one type of atom. Why is it that most of the substances found on earth are compounds? Why do atoms usually associate with other atoms instead of existing alone? In this chapter, you will explore why atoms form chemical bonds to make molecules and compounds.

Investigations for Chapter 19

19.1	**Chemical Bonds**	*Why do atoms form chemical bonds?*

In this Investigation, you will build models of atoms and discover one of the fundamental ideas in chemistry: How electrons are involved in the formation of chemical bonds.

19.2	**Chemical Formulas**	*Why do atoms combine in certain ratios?*

In this Investigation, you will discover how the arrangement of electrons in atoms is related to groups on the periodic table. You will also learn why atoms form chemical bonds with other atoms in certain ratios.

19.3	**Comparing Molecules**	*How can you determine the chemical formula of a compound?*

Atoms combine in whole number ratios to form chemical compounds. In fact, the same two elements may form several different compounds by combining in different ratios. Chemical formulas show the ratios in which elements combine to form a compound. In this Investigation, you will use nuts and bolts to illustrate the meaning of chemical formulas.

Learning Goals

In this chapter, you will:

- ✔ Relate the chemical behavior of an element, including bonding, to its placement on the periodic table.
- ✔ Explain how elements form chemical bonds and the identify the role of electrons in bonding.
- ✔ Predict the chemical formulas of compounds made up of two different elements.
- ✔ Write chemical formulas for compounds made up of many different types of elements.
- ✔ Calculate the formula mass of a compound and compare different compounds based on their formula masses.
- ✔ Identify the environmental and economic impact of recycling plastics.

Vocabulary

Avogadro number	diatomic molecule	ion	polymer
chemical bond	energy level	monoatomic ion	react
chemical formula	formula mass	octet	subscript
covalent bond	ionic bond	polyatomic ion	valence electron

19.1 Chemical Bonds

Most of the matter around you and inside of you is in the form of compounds. For example, your body is about 80 percent water. You learned in the last unit that water, H_2O, is made up of hydrogen and oxygen atoms combined in a 2:1 ratio. If a substance is made of a pure element, like an iron nail, chances are (with the exception of the noble gases) it will eventually react with another element or compound to become something else. Why does iron rust? Why is the Statue of Liberty green, even though it is made of copper? The answer is simple: Most atoms are unstable unless they are combined with other atoms. When atoms of different elements combine to make compounds, they form chemical bonds. A chemical bond forms when atoms exchange or share electrons.

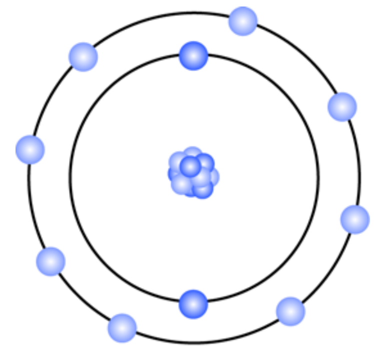


Figure 19.1: *A neon atom has a complete octet, or eight valence electrons.*

Valence electrons and the octet rule

The outer electrons are involved in bonding

Electrons in atoms are found in energy levels surrounding the nucleus in the form of an electron cloud. The higher the energy level, the more energy is required in order for an electron to occupy that part of the electron cloud. The outermost energy level contains the valence electrons and is called the *valence shell*. The maximum number of valence electrons that an atom can have is *eight*. The exception to this rule is the first energy level, which only holds *two* electrons. *Valence electrons are the ones involved in forming chemical bonds.*

The octet rule

When an atom has eight valence electrons, it is said to have an octet of electrons. Figure 19.1 shows neon with a complete octet. In order to achieve this octet, atoms will lose, gain, or share electrons. An atom with a complete octet, like neon has lower energy and is more stable than an atom with an incomplete octet, like sodium (Figure 19.2). Atoms form chemical bonds with other atoms by either sharing electrons, or transferring them in order to complete their octet and move to a lower energy state. This is known as the octet rule.

Atoms form chemical bonds with other atoms by sharing or transferring electrons to have a complete set of eight valence electrons.

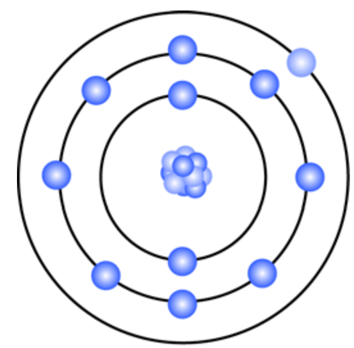


Figure 19.2: *A sodium atom an incomplete octet with only one valence electron.*

Exceptions to the octet rule

Some atoms are an exception to the octet rule. Why? Remember, the first energy level only needs two electrons, not eight. Hydrogen, with only one electron, needs only one more to fill its valence shell. Helium, with two electrons, has a full valence shell (Figure 19.3). This means that helium is chemically stable and does not bond with other atoms.

Stable atoms have full valence shells

What about lithium? It has three electrons. This means that its first shell is full but there is one extra electron in the second shell. Would it be easier for lithium (Figure 19.4) to gain seven electrons to fill the second shell—or to lose one electron? You probably would guess that it is easier to lose one electron that gain seven. You would be correct in your guess, for lithium loses one electron when it bonds with other atoms. Table 19.1 shows the number of valence electrons and the number needed to complete the octet for the first 18 elements.

Table 19.1: ***Elements, number of valence electrons, and number needed to complete the octet***

element	valence electrons	number needed	element	valence electrons	number needed
H	1	**1**	**Ne**	8	**0**
He	2	**0**	**Na**	1	**7**
Li	1	**7**	**Mg**	2	**6**
Be	2	**6**	**Al**	3	**5**
B	3	**5**	**Si**	4	**4**
C	4	**4**	**P**	5	**3**
N	5	**3**	**S**	6	**2**
O	6	**2**	**Cl**	7	**1**
F	7	**1**	**Ar**	8	**0**

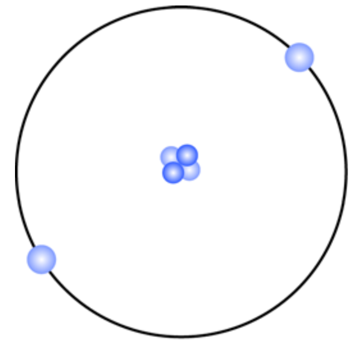


Figure 19.3: *Helium atoms have only two electrons, both of which are in the outermost level. Helium is an exception to the octet rule.*

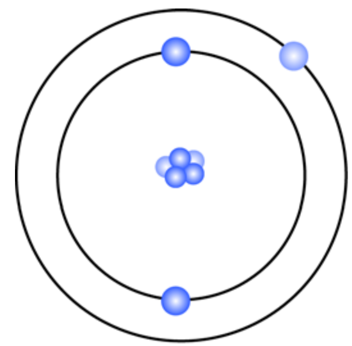


Figure 19.4: *Lithium atoms have three electrons. Since the first energy level only holds two electrons, lithium has one valence electron. If lithium loses that electron, it will have a full valence shell with two electrons.*

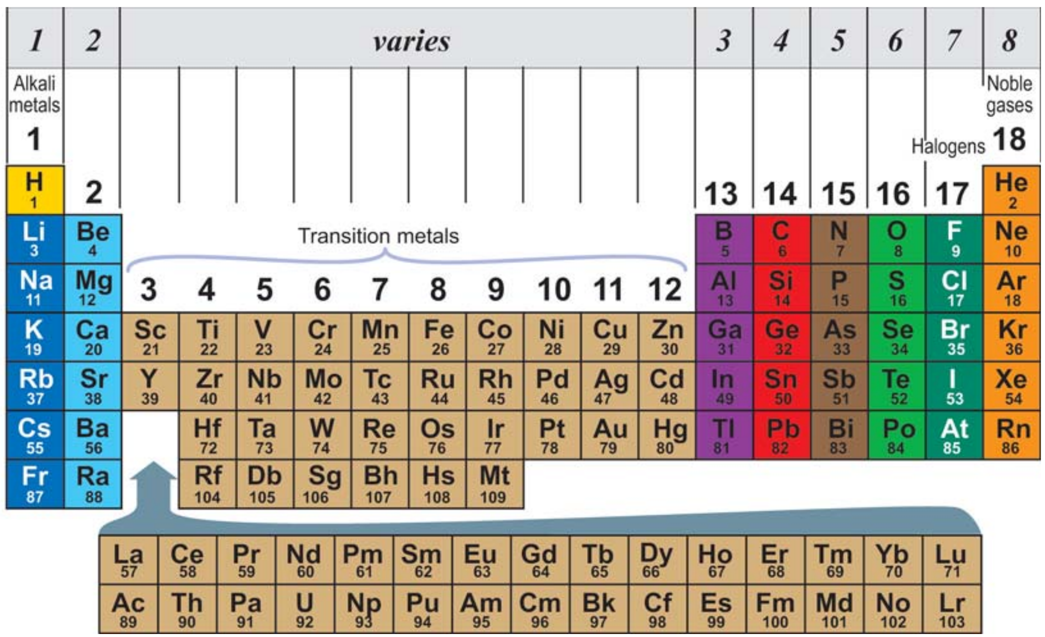
Electrons and the periodic table

Valence and the periodic table The periodic table arranges elements from left to right by the number of valence electrons. The alkali metals (group 1) have one valence electron. Group 2 elements have two valence electrons. Group 17 elements have seven valence electrons. These elements are called *halogens*. The halogens are very reactive since they only need to gain one electron to get to eight valence electrons. The *noble gases* (group 18) have no valence electrons and do not form chemical bonds with other atoms.

Transition metals The elements in groups 3 to 12 are called the **transition metals**. These elements have electrons in the fourth and fifth energy levels. The bonding patterns for transition metals are more complex because of the large number of electrons in the highest unfilled level.

Number of valence electrons

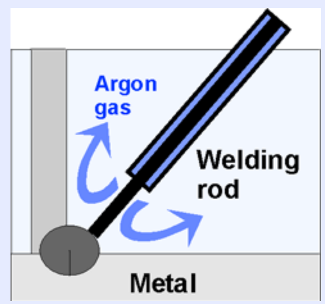
Periodic table of the elements



Noble gases are useful

Argon, a noble gas, is used in welding metal because it makes no chemical bonds. When metal is hot, it reacts quickly with oxygen in the air to form oxides, like rust. The oxides greatly reduce the strength of the metal.

A Metal Inert Gas (MIG) welder uses a flow of argon gas to keep oxygen away. The argon gas flows through a tube around the tip of the welder's rod. The hot area around the tip of the welding rod is kept free of oxygen and strong welds can be made without oxides.



Why chemical bonds form

Atoms form bonds to reach lower energy

Chemical bonds are a form of potential energy. Imagine pulling adhesive tape off a surface. It takes energy to separate atoms that are bonded together just like it takes energy to pull tape off a surface. If it takes energy to separate bonded atoms, then the same energy must be released when the bond is formed. This is a direct consequence of the law of conservation of energy. Energy is released when atoms form chemical bonds. The atoms in matter are usually chemically bonded to other atoms because chemically bonded atoms have lower energy than free atoms. Like a ball rolling downhill, systems in nature tend to settle into the configuration of lowest energy.

Atoms bond to get eight valence electrons

Atoms are most stable when they have either 2 or 8 valence electrons. The noble gases already have eight, so they are stable and do not form bonds with other atoms. Other atoms form chemical bonds so that they can share electrons to reach that stable number of eight. The Lewis dot diagram (Figure 19.5) shows the element symbol surrounded by one to eight dots representing the valence electrons. Carbon has four dots, hydrogen one. One carbon atom bonds with four hydrogen atoms because this molecule (methane) allows the carbon atom to have eight valence electrons—four of its own and four shared with hydrogen atoms.

Molecules with oxygen

Oxygen has six valence electrons. That means oxygen needs two more electrons to get to eight. One oxygen atom bonded with two hydrogen atoms (water) is one way to make eight. One oxygen atom can also bond with one beryllium atom to make eight. Beryllium has two valence electrons. Complex molecules are formed by multiple atoms sharing valence electrons so that each one can achieve the required number of eight.

Some elements prefer to lose electrons

Some elements can achieve the stable eight electrons more easily by losing an electron than by gaining one. Sodium (Na) is a good example of this type of element. It has a full eight electrons in the second level, and one valence electron in the third level. If the single valence electron is given away, sodium is left with a stable eight electrons in the (full) second level. For this reason, sodium tends to form bonds that allow it to give up its single valence electron.

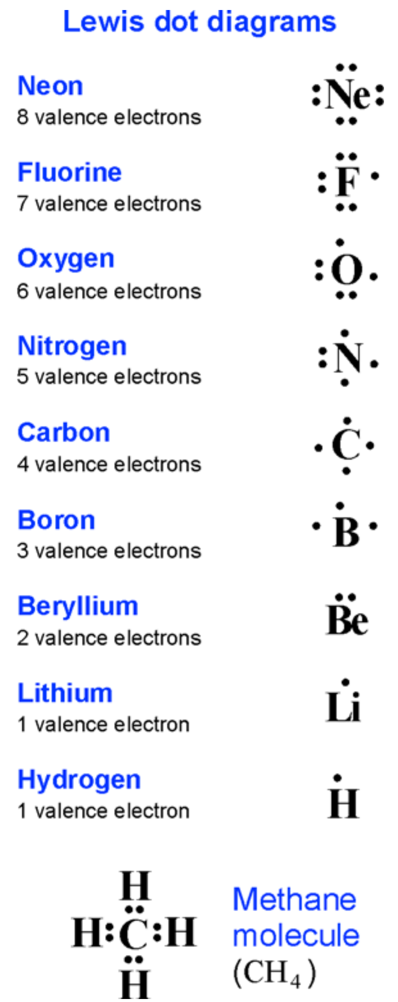


Figure 19.5: *Lewis dot diagrams show valence electrons as dots around the element symbol. Atoms form bonds to get eight valence electrons by sharing with other atoms.*

Ionic and covalent bonds

Ionic bonds Most chemical bonds fall into two categories, depending on whether the valence electrons are transferred or shared. Electrons in an ionic bond are transferred from one atom to another. Atoms that either gain or lose an electron become ions. Ions may have either positive or negative electric charge. The atom which takes the electron acquires an overall negative charge. The positive and negative ions are attracted to each other, creating the bond. Ionic bonds tend to form between more than one pair of atoms at a time. The bond between sodium (Na) and chlorine (Cl) in sodium chloride (salt) is a good example of an ionic bond. In a crystal of salt each sodium ion is attracted to all the neighboring chlorine ions (Figure 19.6).

Covalent bonds In a covalent bond the electrons are *shared* between atoms. The bonds between hydrogen and carbon in a methane molecule are covalent bonds. The electrons in a covalent bond act like ties between the two atoms. An important difference between covalent and ionic bonds is that covalent bonds act only between the atoms in a single *molecule*, while ionic bonds act between all adjacent atoms (ions).

Alkali metals tend to form ionic bonds Whether a covalent or ionic bond is formed depends on how close each atom is to the stable number of eight valence electrons. The alkali metals with one valence electron have a high tendency to give up an electron. The halogen elements with seven valence electrons have a high tendency to take an electron. If you put an alkali (Na) with a halogen (Cl), you get an ionic bond because one atom *strongly* wants to lose an electron and the other *strongly* wants to gain one.

Examples of covalent bonds Elements that have two to six valence electrons tend to form covalent bonds with each other since the tendency to take or receive electrons is more matched. For example, all the bonds in silicon dioxide (glass) are covalent bonds between silicon and oxygen atoms. Diamonds are the hardest substance known. A diamond is a pure carbon crystal in which every carbon atom is joined to four other carbon atoms by a covalent bond (Figure 19.7). The hardness of diamonds is due to the fact that four covalent bonds must be broken to move each carbon atom.

Figure 19.6: *The ionic bonds in a salt crystal (NaCl) come from electrical attraction between negative chlorine ions and positive sodium ions.*

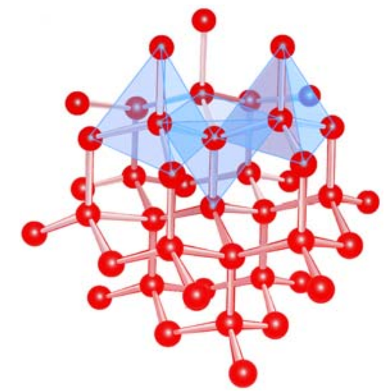


Figure 19.7: *A diamond crystal is made of pure carbon connected by a strong network of covalent bonds.*

The formation of bonds

Chemical bonds make compounds with different properties

Sodium is a soft, silvery metal that is so reactive, it must be stored so it does not come in contact with the air. Chlorine exists as a yellowish-green gas that is very poisonous. When atoms of these two elements chemically bond, they become the white crystals that you use to make your food taste better—salt! This compound is also known as sodium chloride. When atoms form chemical bonds, the properties of the resulting compound are usually very different than the properties of the elements from which they are made.

The formation of an ionic bond

A neutral sodium atom has 11 positively charged protons and 11 negatively charged electrons. When sodium loses one electron, it has 11 protons (+) and 10 electrons (-) and becomes an ion with a net charge of +1. This is because it now has one more positive charge than negative charges (Figure 19.8). A neutral chlorine atom has 17 protons and 17 neutrons. When chlorine gains one electron to complete its stable octet, it has 17 protons (+) and 18 electrons (-) and becomes an ion with a charge of -1. This is because it has gained one negative charge (Figure 19.9).

Opposites attract

Because the sodium ion has a positive charge and the chlorine ion has a negative charge, the two atoms become attracted to each other and form an ionic bond. Recall that opposite charges attract. When sodium, with its +1 charge, comes into contact with chlorine, with its -1 charge, they become electrically neutral as long as they are together. This is because +1 and -1 cancel each other out. This also explains why sodium and chlorine combine in a 1:1 ratio to make sodium chloride (Figure 19.10).

Covalent bonds and diatomic molecules

Covalent bonds can form between two different types of atoms, or between two or more atoms of the same type. For example, chlorine, with seven valence electrons, sometimes shares an electron with another chlorine atom. With this configuration, both atoms can share an electron through a covalent bond to become more stable (shown left). Many elemental gases in our atmosphere exist in pairs of covalently bonded atoms. The gases nitrogen (N_2), oxygen (O_2) and hydrogen (H_2) are a few examples. We call these covalently bonded atoms of the same type **diatomic molecules**.

Figure 19.8: *When a sodium atom loses its valence electron, its net electric charge is +1.*

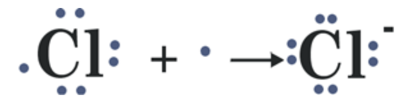


Figure 19.9: *When a chlorine atom gains one electron, its net electric charge is -1.*

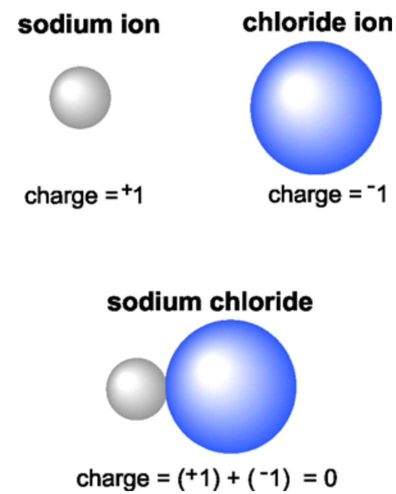


Figure 19.10: *When a sodium ion and a chlorine ion form an ionic bond, the net electric charge is zero (neutral).*

Environmental Issue: Paper or plastic?

What is plastic?

Plastics are **polymers**. You may already know that the prefix *poly-* means "many" and the suffix *-mer* means "unit." A polymer is a large molecule that is composed of repeating smaller molecules. The building block or subunit of synthetic plastics is a molecule called ethylene (Figure 19.11). Paper is made out of a natural polymer called cellulose. Cellulose, the most abundant polymer on Earth, is made out of many subunits of glucose molecules. The difference between a natural polymer like cellulose, and the man-made polymer that is used to make a bag or a soda bottle is that cellulose is easily digested by microorganisms. In contrast, synthetic plastics are not easily broken down. For this reason, when you throw a plastic cup away, there isn't much chance it will decompose quickly or at all.

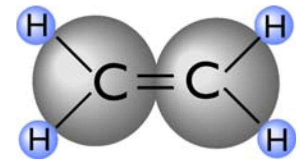


Figure 19.11: *The ethylene molecule is the building block, or subunit, of synthetic plastics. That is why plastics are often referred to as "polyethylenes."*

Why can't microorganisms digest plastic?

In order for microorganisms to be able to break down a plastic molecule, they must have access to an exposed end or side branch of the molecule. Because synthetic plastics are such long chains of carbon surrounded by hydrogens, there are no places for microorganisms to begin "biting" on the molecule. Since most plastics we use are man-made, microorganisms are not able to consume them.

Biodegradable plastics

One way to approach the plastics problem is to make them *biodegradable*. This means that microbes such as bacteria and fungi can "eat" the plastic. Making biodegradable plastics involves creating exposed ends on the molecules so microbes can get a start. This is done by inserting a food item that microbes readily eat into a plastic. For instance, starch can be inserted in the polyethylene molecule (Figure 19.12). Once microbes have eaten the starch, two ends of polyethylene are exposed. Many plastic grocery bags contain starch.

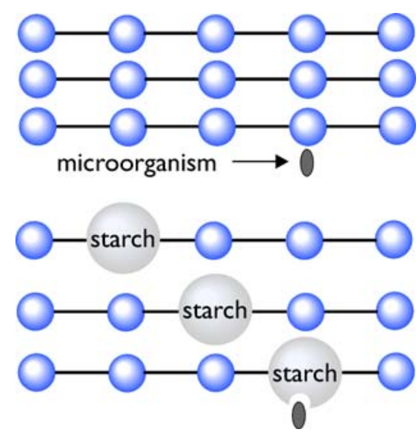


Figure 19.12: *Inserting starch molecules into the polyethylene chain provides a place for microorganisms to begin breaking it down.*

Recycling plastics

You may be familiar with the recycling symbols on the bottoms of plastic bottles. Those symbols allow you to sort the different plastics that make up each kind of plastic. Choosing the kind of plastic that is used for a certain product is a careful decision. Think about the wide variety of plastic containers (and don't forget their lids) that are used for certain products. In order to recycle plastic, you need to melt it so that it can be remolded into new containers or extruded into a kind of fabric that is used for sweatshirts.

19.2 Chemical Formulas

In the previous section, you learned how and why atoms form chemical bonds with one another. You also know that atoms combine in certain ratios with other atoms. These ratios determine the chemical formula for a compound. In this section, you will learn how to write the chemical formulas for compounds. You will also learn how to name compounds based on their chemical formulas.

Chemical formulas and oxidation numbers

Ionic compounds

Recall that sodium atoms form *ionic bonds* with chlorine atoms to make sodium chloride. Because sodium chloride is a compound made out of ions, it is called an ionic compound. The chemical formula for sodium chloride is NaCl. This formula indicates that every formula unit of sodium chloride contains one atom of sodium and one atom of chlorine, a 1:1 ratio.

Why do sodium and chlorine combine in a 1:1 ratio? When sodium loses one electron, it becomes an ion with a charge of +1. When chlorine gains an electron, it becomes an ion with a charge of -1. When these two ions combine to form an ionic bond, the net electrical charge is zero. This is because (+1) + (-1) = 0.

All compounds have an electrical charge of zero; that is, they are neutral.

Oxidation numbers

A sodium atom always ionizes to become Na+ (a charge of +1) when it combines with other atoms to make a compound. Therefore, we say that *sodium has an oxidation number of 1+*. An oxidation number indicates how many electrons are lost, gained, or shared when bonding occurs. Notice that the convention for writing oxidation numbers is the opposite of the convention for writing the charge. When writing the oxidation number, the positive (or negative) symbol is written *after* the number, not *before* it.

What is chlorine's oxidation number? If you think it is 1-, you are right. This is because chlorine gains one electron, one negative charge, when it bonds with other atoms. Figure 19.14 shows the oxidation numbers for some of the elements.

Figure 19.13: *All compounds have en electrical charge of zero. In the case of sodium chloride, sodium ions (+1) and chlorine ions (-1) combine in a 1:1 ratio. This means that there is one sodium ion for every chlorine ion in the compound.*

atom	electrons gained or lost	oxidation number
K	loses 1	1+
Mg	loses 2	2+
Al	loses 3	3+
P	gains 3	3-
Se	gains 2	2-
Br	gains 1	1-
Ar	loses 0	0

Figure 19.14: *Oxidation numbers of some common elements.*

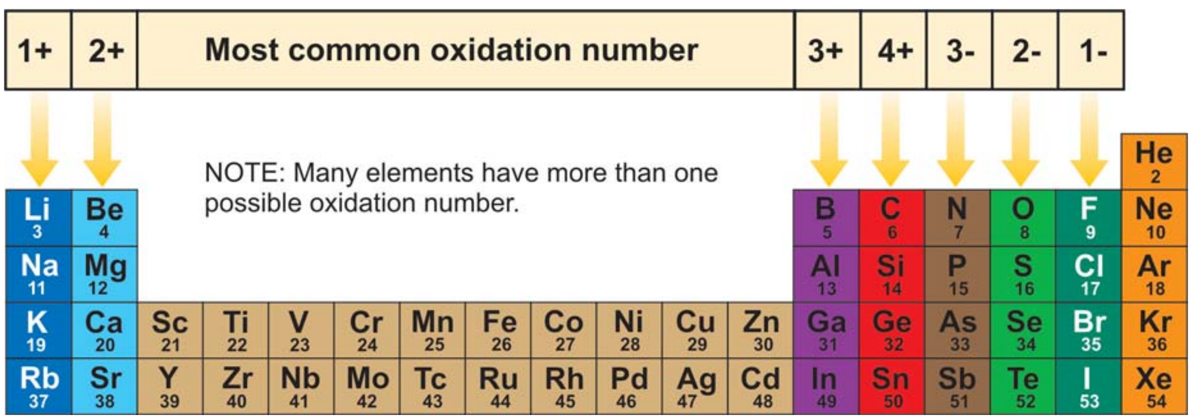
Predicting oxidation numbers from the periodic table

In the last section, you learned that you can tell how many valence electrons an element has by its placement on the periodic table. If you can determine how many valence electrons an element has, you can predict its oxidation number. For example, locate beryllium (Be) on the periodic table below. It is in the second column, or Group 2, which means beryllium has two valence electrons. Will beryllium get rid of two electrons, or gain six in order to obtain a stable octet? Of course, it is easier to lose two electrons. When these two electrons are lost, beryllium becomes an ion with a charge of +2. Therefore, the most common oxidation number for beryllium is 2+. In fact, the most common oxidation number for all elements in Group 2 is 2+. Table 19.2 shows some common oxidation numbers.

Table 19.2: ***Some oxidation numbers***

atom	electrons gained or lost	oxidation number
K	loses 1	1+
Mg	loses 2	2+
Al	loses 3	3+
P	gains 3	3-
Se	gains 2	2-
Br	gains 1	1-
Ar	loses 0	0

The periodic table below shows the most common oxidation numbers of most of the elements. The elements known as transition metals (in the middle of the table) have variable oxidation numbers.



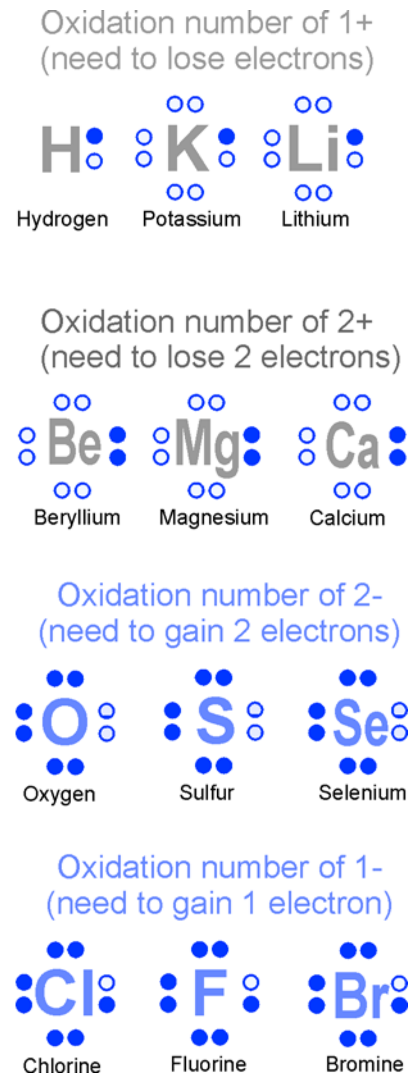


Figure 19.15: *Oxidation number corresponds to the need to gain or lose electrons.*

Writing the chemical formulas of ionic compounds.

Monoatomic ions

Both sodium and chlorine ions are **monoatomic ions**, that is, ions that consist of a single atom. It's easy to write the chemical formula for compounds made of monatomic ions, if you follow these rules:

1	Write the symbol for the monoatomic ion that has a ***positive*** charge first.
2	Write the symbol for the monatomic ion that has a ***negative*** charge second.
3	Add **subscripts** below each element symbol so that the sum of the positive and negative oxidation numbers is equal to zero—a neutral compound, remember? Subscripts tell you how many atoms of each element are in the compound.

Some elements have more than one oxidation number. In this case, roman numerals are used to distinguish the oxidation number. Figure 19.16 shows a few of these elements.

element	oxidation number
copper (I)	Cu^{+}
copper (II)	Cu^{2+}
iron (II)	Fe^{2+}
iron (III)	Fe^{3+}
chromium (II)	Cr^{2+}
chromium (III)	Cr^{3+}
lead (II)	Pb^{2+}
lead (IV)	Pb^{4+}

Figure 19.16: *Elements with variable oxidation numbers.*

Example: Writing a chemical formula

Write the formula for a compound that is made of iron (III) and oxygen.

1. Find the oxidation numbers of each element in the compound.

Iron (III) is a transition metal. The roman numbers indicate that it has an oxidation number of 3+. Its formula is Fe^{3+}.

Oxygen is in group 16 of the periodic table and has an oxidation number of 2-. Its formula is O^{2-}.

2. Determine the ratios of each element and write the chemical formula.

If one iron (III) ion bonds with one oxygen ion, will the compound be neutral? No, since 3+ added to 2- equals 1+. If you have two iron (III) ions for every three oxygen ions, what happens? 2(3+) added to 3(2-) is equal to 0. This means that three iron (III) ions bond with two oxygen ions to get a neutral compound.\

The formula for a compound of iron (III) and oxygen is Fe_2O_3.

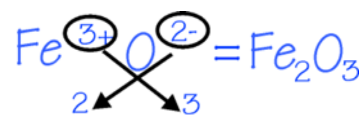


Figure 19.17: *The criss-cross method is a simple way to determine the chemical formula of a compound.*

Ionic compounds made of more than two types of atoms

Not all compounds are made of only two types of atoms

Have you ever taken an antacid for an upset stomach? Many antacids contain calcium carbonate, or $CaCO_3$. How many types of atoms does this compound contain? You are right if you said three: calcium, carbon, and oxygen. Some ionic compounds contain **polyatomic ions**. Polyatomic ions contain more than one type of atom. The prefix *poly* means "many." Table 19.3 lists some common polyatomic ions.

Table 19.3: ***Polyatomic ions***

oxidation no.	name	formula
1+	ammonium	NH_4^+
1-	acetate	$C_2H_3O_2^-$
2-	carbonate	CO_3^{2-}
2-	chromate	CrO_4^{2-}
1-	hydrogen carbonate	HCO_3^-
1+	hydronium	H_3O^+
1-	hydroxide	OH^-
1-	nitrate	NO_3^-
2-	peroxide	O_2^{2-}
3-	phosphate	PO_4^{3-}
2-	sulfate	SO_4^{2-}
2-	sulfite	SO_3^{2-}

The positive ion is Ca^{2+} This is a *monoatomic* ion. You can determine its oxidation number by looking at the periodic table.
The negative ion is CO_3^{2-} This is a *polyatomic* ion. You can determine its oxidation number by looking at the ion chart (Table 19.2).

Figure 19.18: *Which ions does $CaCO_3$ contain?*

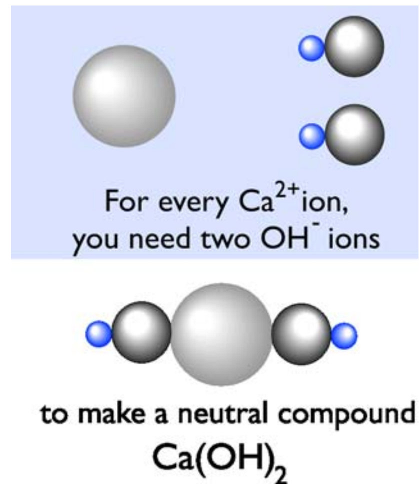


Figure 19.19: *How to write the chemical formula for calcium hydroxide.*

Rules for writing chemical formulas of ionic compounds that contain polyatomic ions

1. Write the chemical formula and oxidation number of the positive ion. If the positive ion is monoatomic, you can find its oxidation number from the periodic table. If the positive ion is polyatomic, use table 19.3 to find the oxidation number of the polyatomic ion.
2. Write the chemical formula and oxidation number for the negative ion. Again, use the periodic table if the negative ion is monoatomic, or table 19.3 if the negative ion is polyatomic.
3. Add the oxidation numbers of the positive and negative ions. Do they add up to zero? If yes, write the formula for the positive ion first and the negative ion second. Do not include the oxidation numbers in the chemical formula. Be sure to write the subscripts!
4. If the oxidation numbers do not add up to zero, figure out how many of each ion you will need so that the oxidation numbers add up to zero. (**Hint:** *Find the least common multiple between the two oxidation numbers. The number that you have to multiply each oxidation number by to equal the least common multiple tells you how many of each ion you need).*

Example: Writing the chemical formula for *aluminum sulfate*

1. Find the formula and charge of the positive ion.

The positive ion is always the first ion in the name. Where can you find the chemical formula for the aluminum ion? Aluminum is monoatomic and its formula is Al. You can find its oxidation number from the periodic table. Al is in group 13 and contains three valence electrons. When it loses those, its charge becomes +3. Therefore, the oxidation number for Al is 3+.

Chemical formula and oxidation number = Al^{3+}

2. Find the formula and charge of the negative ion.

Sulfate is the negative ion. Where can you find the chemical formula and oxidation number for the sulfate ion? Since sulfate is a polyatomic ion, you must consult an ion chart, unless you can remember the formulas and oxidation numbers for all ions!

Chemical formula and oxidation number = SO_4^{2-}

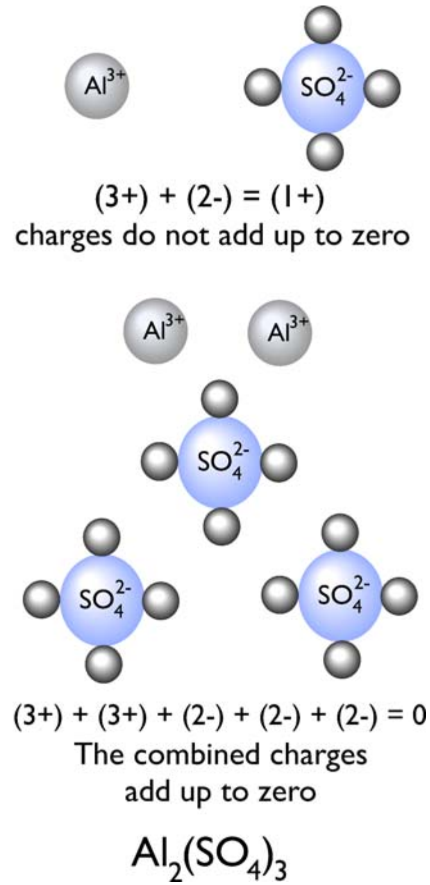


Figure 19.20: *This diagram shows how to determine the chemical formula for aluminum sulfate. How many of each ion does the formula indicate? How many atoms of each element are in one formula unit of aluminum sulfate?*

Example, continued

3. Determine how many of each ion are needed so the charges are equal to zero.

The oxidation numbers of (3+) and (2-) add up to (1+), not zero. (3+) + (2-) = (1-)
You need 2 aluminum ions and 3 sulfate ions to make the charges add up to zero.

$(Al^{3+}) \times (2) = (6+)$ $(SO_4^{2-}) \times (3) = (6-)$

4. Write the chemical formula for the compound.

Write the formula, enclosing sulfate in parentheses. Do not change subscripts in the ion.

$Al_2(SO_4)_3$

Example: Name BaF_2

1 The first element is barium.

2 The second element is fluorine.

3 The compound's name is barium fluoride.

Figure 19.21: *How to name an ionic compound that is made of two monoatomic ions.*

How do you name ionic compounds?

Compounds with only monoatomic ions

Naming compounds with only monoatomic ions is very simple if you follow the rules below. Figure 19.21 shows an example.

1	Write the name of the first element in the compound.
2	Write the root name of the second element. For example, ***chlor-*** is the root name of ***chlorine***. Simply subtract the ***-ine*** ending.
3	Add the ending ***-ide*** to the root name. ***Chlor-*** becomes ***chloride***.

Compounds that contain polyatomic ions

To name a compound that contains polyatomic ions, follow these steps.

1	Write the name of the positive ion first. Use the periodic table or an ion chart to find its name.
2	Write the name of the negative ion second. Use the periodic table or an ion chart to find its name.

1	The positive ion, Mg^{2+}, is **magnesium**.
2	The negative ion, CO_3^{2-}, is **carbonate**.
3	The name of the compound is **magnesium carbonate**.

Figure 19.22: *How to name a compound with the chemical formula $MgCO_3$.*

Covalent compounds

Covalent compounds consist of molecules

Compounds that are formed through covalent bonds (shared electrons) are called covalent compounds. Covalent compounds are sometimes referred to as *molecular compounds* because covalent bonding produces molecules. Ionic bonding does not produce molecules but groups of positively- and negatively-charged ions that attract each other. Each individual group is called a *formula unit*.

Naming covalent compounds

Covalent compounds that are made of more than two types of elements have their own special naming system that you will learn about in more advanced chemistry courses. Naming covalent compounds that consist of only two elements, often called binary compounds, is fairly straightforward. This naming is very similar to the methods used in naming ionic compounds that contain only two elements described on page 342. However, in this case, the *number* of each type of atom is specified in the name of the compound. Figure 19.23 shows how to name a binary covalent compound.

The Greek prefixes in Figure 19.24 are used in naming binary covalent compounds. If the molecule contains only one atom of the first element, the prefix *mono-* is not used. It is used in the name of the second element in the compound as in the example below:

CO
carbon monoxide

CO_2
carbon dioxide

Empirical and molecular formula

The simplest whole-number ratios by which elements combine are written in a form called the empirical formula. The actual number of atoms of each element in the compound is written in a form called the molecular formula. For some compounds, the empirical formula and the molecular formula are the same as is the case with water, H_2O. A molecule of the sugar glucose has a molecular formula of $C_6H_{12}O_6$. To find the empirical formula of glucose, calculate the simplest whole number ratio of the atoms. The empirical formula for glucose is CH_2O.

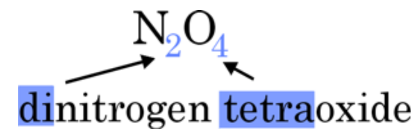


Figure 19.23: *To name a binary covalent compound, specify the number of each type of atom using a Greek prefix. The ending of the name of the second element in the compound is modified by adding the suffix -ide.*

prefix	meaning
mono-	1
di-	2
tri-	3
tetra-	4
penta-	5
hexa-	6
hepta-	7
octa-	8
nona-	9

Figure 19.24: *Greek prefixes used in naming binary covalent compounds.*

19.3 Comparing Molecules

If you have ever bought paper, you know that it is sometimes sold in a package of 500 sheets called a *ream*. Do you think someone in a factory counts individual sheets of paper and packages them for sale? Instead of counting individual sheets, the paper is packaged according to *mass*. Knowing the mass of 500 sheets of paper allows the paper to be packaged quickly and efficiently by machines. If the machines that make the paper suddenly started making sheets that were twice as heavy, what would happen to the number of sheets in a package? "Counting" by mass is a useful way to deal with large numbers of objects that are uniform in size—like atoms in an element or molecules in a compound. In this section, you will learn how to quantify atoms and molecules using mass.

Figure 19.25: *Paper in a factory is packaged by mass instead of by counting.*

Comparing a water molecule to a formula unit of calcium carbonate

A water molecule has a different mass than a unit of calcium carbonate

Does a molecule of *water* (H_2O) have the same mass as a group of atoms (called a *formula unit*) that make up the ionic compound *calcium carbonate* ($CaCO_3$)? Figure 19.26 shows the comparative sizes of each. This question seems difficult to answer at first because atoms are so small that you cannot see them. However, you *can* use what you have learned so far to answer the question. You know that atoms of different elements have different *atomic masses*. You also know that compounds are made of different numbers and types of atoms. Based on this knowledge, you can logically conclude that a molecule of water would have a *different* mass than a formula unit of calcium carbonate.

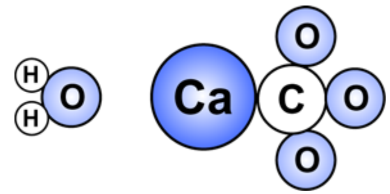


Figure 19.26: *Do you think that a molecule of water has the same mass as a formula unit of calcium carbonate?*

Atomic mass units

All atoms are assigned a unit of relative mass known as the *atomic mass unit,* or amu. Atomic mass units allow us to compare quantities of matter even though we can't see the molecules and atoms that we want to count or measure.

How is atomic mass determined?

Carbon atoms are used as a standard for determining the atomic mass units for the other elements on the periodic table. One carbon atom is equivalent to 12.01 atomic mass units. Because one hydrogen atom is about 1/12 the mass of one carbon atom (Figure 19.27), it is represented as having 1.01 atomic mass units. The actual mass of one atomic mass unit is 1.6606 x 10^{-24} grams—a very small amount!

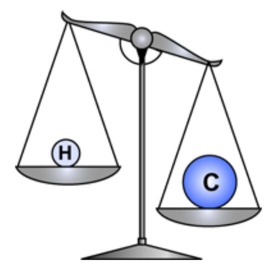


Figure 19.27: *One hydrogen atom is 1/12th the mass of one carbon atom.*

Chemical formulas and formula mass

Different objects can be compared by using relative mass

We can use an analogy to explain how the concept of relative mass can be used. Let's say that we have the same number of gumdrops and jawbreakers, and that we will use the variable "*x*" to represent this number. The sample of *x* gumdrops has a mass of 100 grams, and the sample of *x* jawbreakers has a mass of 400 grams. This means that an individual gumdrop has a mass that is 1/4, or 25 percent of, the mass of a jawbreaker. Twenty-five percent can be represented by the number 0.25. This number represents the relative mass of a gumdrop compared with a jawbreaker. Let's call the jawbreaker unit of mass a jmu, for "jawbreaker mass unit." Now, if a single jawbreaker has a mass of 1.0 jmu, then a gumdrop would have a mass of 0.25 jmu. How many jawbreaker mass units would *x* number of candy bars be if they weighed 800 grams? They would have a mass of 2 jmu.

Chemical formulas

A chemical formula for a compound gives you three useful pieces of information. First, it tells you which types of atoms and how many of each are present in a compound. Second, it lets you know if polyatomic ions are present. Remember that polyatomic ions are distinct groups of atoms with a collective oxidation number. For example, NO_3^- is a polyatomic ion called nitrate with an oxidation number of 1-. As you practice writing chemical formulas, you will start to recognize these ions.

What is formula mass?

Third, a chemical formula allows you to calculate the mass of one unit of the compound *relative* to the mass of other compounds. Formula mass, like atomic mass, is a way to compare the masses of units of different compounds. The formula mass of a compound is determined by adding up the atomic masses of all of the atoms in the compound as shown in Figure 19.29.

Figuring formula mass

The formula for water is H_2O. This means that there are two hydrogen atoms for every one of oxygen in a molecule of water. Using the periodic table, you can see that the atomic mass of hydrogen is 1.007 amu. For our purposes, we will round all atomic masses to the hundredths place. Using 1.01 amu for hydrogen, we can multiply this number by the number of atoms present to determine atomic mass of hydrogen in a water molecule. The atomic mass of oxygen, rounded off, is 16.00. Using this information, the formula mass for water is calculated.

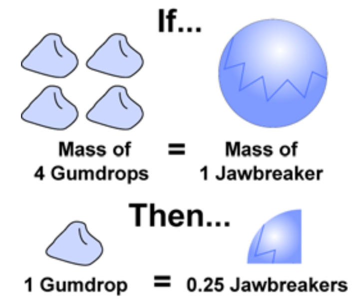


Figure 19.28: *If a single jawbreaker has a mass of 1 jmu (jawbreaker mass unit), what would the mass of 1 gum drop be in jmu?*

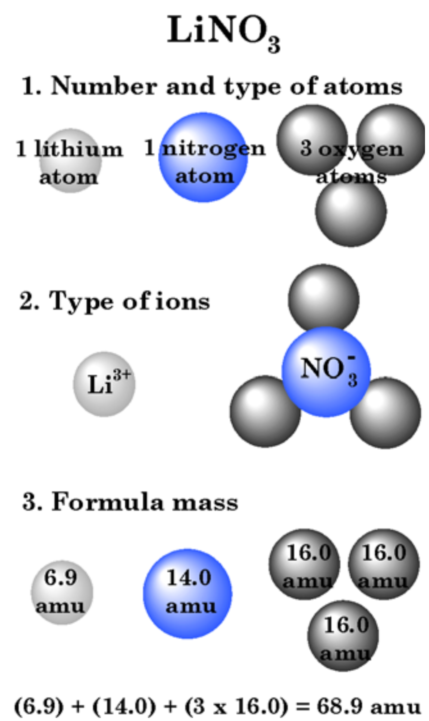


Figure 19.29: *What does a chemical formula tell you?*

How do we make atomic mass units useful to work with?

Atomic mass units and grams

Working with atomic mass units would be very difficult because each atomic mass unit has a mass of 1/12th the mass of a carbon atom. In order to make atomic mass units useful for conducting, using, and evaluating chemical reactions, it would be convenient to set the value of one amu to equal one gram. One gram is, after all, an amount of matter that we can see! For example, one paper clip has a mass of about 2.5 grams.

How do you relate molecules, atomic mass units, and grams?

The mass of one water molecule in atomic mass units is 18.02. How many molecules of water would be in 18.02 *grams* of water? To find out, we need to come up with a *number* of molecules or atoms in a sample that is equal to the atomic mass, in grams. From here forward, we will say that 18.02 grams of water contains the Avogadro number of molecules. This number is 6.02×10^{23}—a very, very large number of molecules! Look at the relationships in Figure 19.30 to help you understand the Avogadro number.

The Avogadro number

The Avogadro number is the number of atoms in the atomic mass of an element or the number of molecules in the formula mass of a compound when these masses are expressed in grams. One set of 6.02×10^{23} atoms or molecules is also referred to as a mole of that substance. The term mole is used to talk about a number of atoms or molecules just like the term *dozen* is used to talk about quantities of eggs, doughnuts, or cans of soda.

The number, 6.02×10^{23}, was named in honor of Count Meadow Avogadro (1776 - 1856), an Italian chemist and physicist who first thought of the concept of the molecule. A German physicist actually discovered the Avogadro number nine years after Avogadro's death.

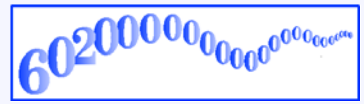
Comparing different compounds

If 6.02×10^{23} water molecules has a mass of 18.02 grams, how much does the same number of formula units of calcium carbonate (an ionic compound) weigh in grams? If we calculate the mass of the same number of molecules or formula units of each substance, we can compare the relative mass of each molecule or unit as shown on the next page.

The formula mass of H_2O is 18.02 amu
18.02 amu = 1 molecule of H_2O
18.02 grams = 6.02×10^{23} molecules of H_2O

Figure 19.30: *The relationship between formula mass, atomic mass units, and grams.*

Science Facts: How large is the Avogadro number?



Imagine that every person on Earth was involved in counting the Avogadro number of atoms. How long do you think it would take? If all 6 billion people counted 3 atoms per second, it would take 1 million years to count 6.02×10^{23} atoms!

Example: Calculating the formula mass of a compound

What is the formula mass of calcium carbonate to the nearest hundredth?

1. Write the chemical formula for the compound.

calcium: Ca^{2+} carbonate: CO_3^{2-}

chemical formula: $CaCO_3$

2. List the atoms, number of each atom, and atomic mass of each atom.

atom	number	atomic mass	total mass (number x atomic mass)
Ca	1	40.08	40.08
C	1	12.01	12.01
O	3	16.00	48.00

3. Add up the values for each type of atom to calculate the formula mass.

40.08 + 12.01 + 48.00 = 100.09 amu

The formula mass of calcium carbonate is 100.09 amu.

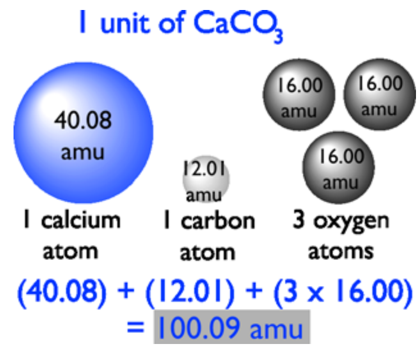


Figure 19.31: *Calculating the formula mass of calcium carbonate.*

How do you compare samples of substances?

The Avogadro number of formula units of calcium carbonate would have a mass of 100.09 grams. In other words, if you used a balance to weigh 100.09 grams of calcium carbonate, there would be 6.02×10^{23} formula units of calcium carbonate in the sample. Likewise, if you used a balance to weigh 18.02 grams of water, there would be 6.02×10^{23} molecules of water in the weighed sample (Figure 19.32).

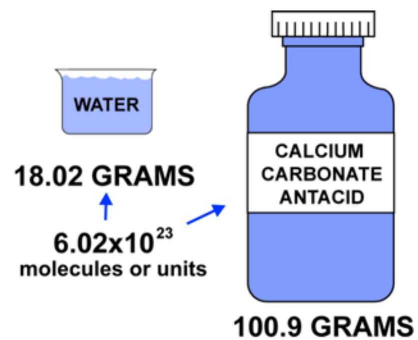


Figure 19.32: *100.09 g of $CaCO_3$ contains 6.02×10^{23} formula units of calcium carbonate. 18.02 g of H_2O contains 6.02×10^{23} molecules of water.*

Hydrates and the chemical formulas

Hydrates are ionic compounds that contain precise numbers of water molecules

Have you ever bought a product that contained in the packaging a packet that was labeled: "Silica gel — do not eat"? These packets are often found inside boxes containing electronics equipment—like a DVD player or a stereo receiver. They are found inside shoeboxes, too. What is the purpose of these packets?

The presence of moisture in the packaging of certain products can be a problem. Manufacturers added packets of silica gel to absorb any such water. Ionic compounds like silicon oxide have the ability to incorporate water molecules as part of their structure. Water molecules become chemically bonded to their ions. A **hydrate** is a compound that has water molecules chemically bonded to its ions. Different compounds can absorb different numbers of molecules of water, as table 19.3 shows.

Table 19.3: ***Common hydrates***

Name	Formula
Silicon oxide monohydrate	$SiO_2 \bullet H_2O$
Barium chloride dihydrate	$BaCl_2 \bullet 2H_2O$
Calcium nitrate tetrahydrate	$Ca(NO_3)_2 \bullet 4H_2O$
Cobalt chloride hexahydrate	$CoCl_2 \bullet 6H_2O$
Magnesium sulfate heptahydrate	$MgSO_4 \bullet 7H_2O$
Iron (III) nitrate nonahydrate	$Fe(NO_3)_3 \bullet 9H_2O$

Note that the chemical formula of a hydrate shows the ionic compound times a certain number of water molecules. This denotes a ratio of the number of molecules of water absorbed for each formula unit of the compound. Note also that the name for each compound is followed by a Greek prefix indicating the number of water molecules and the word "hydrate." Figure 19.33 lists some Greek prefixes and their meanings.

prefix	meaning
mono-	1
di-	2
tri-	3
tetra-	4
penta-	5
hexa-	6
hepta-	7
octa-	8
nona-	9

Figure 19.33: *Greek prefixes.*

Getting rid of the water molecules

You can remove the water molecules from a hydrate by heating it. When all the water leaves the hydrate through evaporation, it is **anhydrous**, a term that means "without water." Now that you know why packets of silica gel are included with some products, how could you *reuse* a packet of silica gel? How would you know when the packet of silica gel was anhydrous?

How do you calculate the formula mass of a hydrate?

It's easy to calculate the formula mass of a hydrate. First, calculate the formula mass of the ionic compound, then add the formula mass of water times as many molecules of water as are present. The example below shows you how to do this step by step.

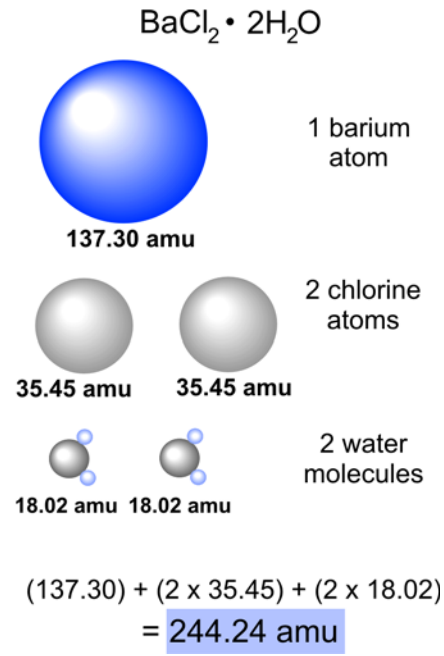


Figure 19.34: *Calculating the formula mass of a hydrate.*

Example: Calculating the formula mass of a hydrate

What is the formula mass of $BaCl_2 \cdot 2H_2O$?

1. Calculate the formula mass of the ionic compound

The ionic compound is $BaCl_2$. To calculate its formula mass:

1 Ba atom × 137.30 amu = 137.30 amu

2 Cl atoms × 35.45 amu = 70.90 amu

137.30 amu + 70.90 amu = 208.20 amu

2. Calculate formula mass of the water molecules

The formula mass for water is:

2 H atoms × 1.01 = 2.02 amu

1 O atom × 16.00 = 16.00 amu

2.02 + 16.00 = 18.02 amu

There are 2 molecules of water in the hydrate. The total formula mass is:

2 molecules H_2O × 18.02 = 36.04 amu

3. Calculate the formula mass of the hydrate

$BaCl_2 \times 2H_2O$ = 208.20+ 36.04 = 244.24 amu

Chapter 19 Review

Vocabulary review

Match the following terms with the correct definition. There is one definition extra in the list that will not match any term.

Set One			
1.	covalent bond	a.	The electrons involved in chemical bonding
2.	ionic bond	b.	Most atoms need eight valence electrons to be stable
3.	octet rule	c.	A bond between atoms in which electrons are lost or gained
4.	valence electrons	d.	A number that represents the number of electrons that are lost or gained in bonding
		e.	A bond between atoms in which electrons are shared

Set Two			
1.	Binary compound	a.	An ion like Na+, K+, or Cl-
2.	Monoatomic ion	b.	Electrons that are involved in bonding
3.	Oxidation number	c.	An ion like CO_3^{2-} or OH^-
4.	Polyatomic ion	d.	A number that indicates how many electrons will be gained or lost during bonding
		e.	A molecule composed of two monatomic ions

Concept review

1. Why do atoms tend to combine with other atoms instead of existing as single atoms?
2. Why are atoms in Group 18 considered to be chemically stable?
3. How can you determine the number of valence electrons by looking at the periodic table?
4. What conditions are met when an atom is chemically stable?
5. What is the major difference between ionic and covalent bonds?
6. Provide one general rule for predicting whether or not a bond will be ionic. (Hint: use the periodic table in your rule.)
7. What are polymers? Give an example of a natural polymer and a synthetic polymer.
8. What is an oxidation number? How can you determine an element's oxidation number by looking at the periodic table?
9. In a chemical formula, what do subscripts tell you?
10. What is the relationship between the formula mass of a compound, the Avogadro number of molecules of that compound, and the mass in grams of the compound?

Problems

1. Fill in the table below.

Element	Atomic number	Valence electrons	Lewis dot diagram
Fluorine			
Oxygen			
Phosphorus			
Carbon			
Beryllium			
Nitrogen			
Sulfur			
Neon			
Silicon			

2. Identify which of the following bonds are ionic and which are covalent. Justify your answer with a sentence.
   a. C-C
   b. Na-Br
   c. C-N
   d. C-O
   e. Ca-Cl

3. Fill in the table below.

Element	Number of valence electrons	Electrons gained or lost during ionization	Oxidation number
Potassium			
Aluminum			
Phosphorus			
Krypton			

4. Which group number on the periodic table is represented by each description?
   a. These atoms form compounds with ions that have an oxidation number of 1^-.
   b. The oxidation state of the atoms in this group is 3^-.
   c. Atoms in this group have four valence electrons in the outermost energy level. The atoms in this group form compounds with ions like H^+, Na^+ and Li^+.
   d. If these ions combined with Al^{3+}, you would need three of them and two aluminum ions in the formula.
   e. Atoms in this group lose two electrons during ionization.

5. Which of the following would be a correct chemical formula for a molecule of N^{3-} and H^+?
   a. HNO_3
   b. H_3N_6
   c. NH_3
   d. NH

6. What is the simplest ratio of carbon to hydrogen to oxygen in a molecule of glucose ($C_6H_{12}O_6$)?
   a. 1:2:1
   b. 6:12:6
   c. 2:4:2
   d. 6:2:6

7. What is the correct name for the compound $NaHCO_3$?
   a. sodium carbonide
   b. sodium hydrogen carbonate
   c. sodium hydrogen carboxide
   d. bicarbonate

8. Which of the following ion pairs would combine in a 1:2 ratio?
   a. NH^{4+} and F^-
   b. Be^{2+} and Cl^-
   c. sodium and hydroxide
   d. hydrogen and phosphate

9. For each of the compounds below, (1) state whether it is an empirical or molecular formula; and (2) write the empirical formula (if it is not already an empirical formula).
   a. CH_2O
   b. $(CH_2)_2(OH)_2$
   c. $C_7H_5NO_3S$
   d. $C_{10}H_8O_4$

10. Name each of the following binary covalent compounds.
    a. N_4O_6
    b. SiO_2
    c. S_2F_{10}
    d. $SbCl_5$

11. Write the chemical formula for the following compounds. Consult Table 19.3, "Polyatomic ions," on page 343 when needed.
    a. Sodium acetate
    b. Aluminum hydroxide
    c. Magnesium sulfate
    d. Ammonium nitrate
    e. Calcium fluoride

12. Calculate the formula mass for the following household compounds. Use the periodic table on the inside back cover.
    a. Lye drain cleaner, NaOH
    b. Epsom salts, $MgSO_4$
    c. Aspirin, $C_9H_8O_4$
    d. Plant fertilizer, $Ca(H_2PO_4)_2$
    e. Dampness absorber, $CaCl_2 \cdot 6H_2O$

13. Give the scientific name of compounds (a), (b), and (e) in question 10. Consult Table 19.3 on page 343.

Applying your knowledge

1. Many of the atoms on the periodic table have more than one oxidation number. You can figure out the oxidation number for these elements if you know at least one of the oxidation numbers in the compound. You only need to figure out what the oxidation number would be to make the molecule neutrally charged. Fill in the oxidation numbers for each of the following molecules.

Chemical formula of compound	Oxidation number for positive ion	Oxidation number for negative ion
SiO_2		2-
PBr_3		1-
$FeCl_3$		1-
CuF_2		1-
N_2O_3		2^-
P_2O_5		2^-

2. Suppose you are working in the lab with the following compounds: NaCl and Al_2O_3.
   a. Would the same number of molecules of each compound have the same mass? Explain your reasoning.
   b. Explain how you would measure out Avogadro's number of molecules (6.02×10^{23}) of each compound.
   c. Why is there a difference in the mass of the exact same number of molecules of each compound?

3. Find out about recycling plastics in your community. Prepare a pamphlet or bulletin board for your school that provides information on how to recycle plastics. The pamphlet or bulletin board should include practical information about recycling plastics including: how to get involved in community organizations, and what types of plastics are recycled. If your school does not recycle plastics, see if you can form a committee to develop and implement a plan.

4. Examine the household chemicals that are used in your own home. Make a list of the products your family uses, the names of the chemicals in each product and the hazards associated with each chemical. Research environmentally friendly alternatives to some of the products your family uses and prepare a brief presentation for your class.

UNIT 7

Changes in Matter

Chapter 20

Chemical Reactions

Introduction to Chapter 20

When you drive a car, the engine is using oxygen and gasoline to produce carbon dioxide and water vapor. This is a chemical reaction that you depend upon to go places. In this chapter, you will learn what happens during a chemical reaction and how chemical reactions obey the laws of conservation.

Investigations for Chapter 20

20.1	**Chemical Changes**	*What is the evidence that a chemical change has occurred?*

You will make a list of the evidence for chemical change by carefully observing a series of chemical reactions.

20.2	**Chemical Equations**	*How do you balance chemical equations?*

You will use the Periodic Table Tiles to learn how to balance chemical equations so that the number and type of atoms that react balance with the number and type of atoms that are produced in a reaction.

20.3	**Conservation of Mass**	*How can you prove that mass is conserved in a chemical reaction?*

You will design your own experiment to prove that what you put into a reaction can be accounted for in the products that are produced.

20.4	**Using Equations as Recipes**	*How can you predict the amount of product in a reaction?*

You will discover an important mathematical relationship that will allow you to predict the amount of product based on the amount of one of the reactants.

Learning Goals

In this chapter, you will:

- ✔ Distinguish between physical and chemical changes in matter using examples from everyday life.
- ✔ Write and balance chemical equations.
- ✔ Investigate and identify the law of conservation of mass.
- ✔ Use chemical equations to predict the amount of product that will be produced in a reaction.
- ✔ Design an experiment to prove conservation of mass.
- ✔ Identify the mathematical relationship between the mass in grams of reactants and products, the coefficients in a balanced equation, and the formula masses of the reactants and products.
- ✔ Identify economic and environmental reasons for recycling tires.

Vocabulary

balance	coefficient	limiting reactant	product
chemical change	conservation of atoms	percent yield	reactant
chemical equation	conservation of mass	physical change	
chemical reaction	excess reactant	polymer	

20.1 Chemical Changes

Have you ever tried to watch rust forming on a car? You have probably noticed a patch of rust getting larger as weeks or months pass, but chances are, you did not actually *see* the rust form. Can you watch an ice cube melt? Yes, but this process happens much faster than a car rusts. Changes in matter are occurring all around you, all of the time. There are different types of changes in matter that happen. The rusting of a car is much different from the melting of ice. We can classify changes in matter as either chemical changes or physical changes.

Figure 20.1: *The process of digestion involves both physical and chemical changes to the food. Chewing breaks food into smaller pieces causing a physical change. In the stomach, acids are produced which cause chemical changes.*

Physical changes

You are what you eat

"You are what you eat." You have heard this many times, but have you ever thought about what it means? How does the food you eat become part of your body? How does the food you eat give you energy? The answer is that the food you eat goes through many *changes* as it passes through your body. The process of breaking food down so that your body can use it is called *digestion*. It involves many different changes to the food, both physical changes and chemical changes.

Physical changes

If you take a bite out of an apple, have you changed the chemical composition of the apple? Of course not. You have only removed a small piece of the apple. Once the piece of apple is in your mouth, you begin to chew it. Chewing does not alter the chemical composition of the apple either. It only breaks the apple into smaller pieces so that you can swallow it easily. Chewing causes a physical change in the apple. A **physical change** is a change that affects only the physical properties of a substance. Those properties include size, shape, and state.

Energy and physical changes

You can change the physical properties of ice by crushing it or by simply letting it melt. In both cases, energy is added to the ice. The only difference between solid water (ice), liquid water, and water vapor is the amount of energy involved in each state. Water vapor is the most energetic form of water. Ice, liquid water, and water vapor all have the exact same chemical composition.

Figure 20.2: *Physical changes affect only the physical properties of a substance.*

Chemical changes

Chemical changes

Is the function of chewing only to make the pieces of apple smaller so that you can swallow them? In fact, another function of chewing is to create lots of available surface area for special chemicals called *enzymes* to cause chemical changes in the apple. A **chemical change** is a change in a substance that involves breaking and reforming of chemical bonds to make one or more different substances. When you begin chewing, glands in your mouth produce *saliva*. An enzyme in your saliva called *amylase* immediately gets to work to break down complex carbohydrate molecules into simpler carbohydrate molecules by breaking bonds. This causes a chemical change in the apple, altering its chemical composition. Your body actually begins the process of digestion in your mouth.

Chemical reactions

After you swallow the bite of apple, it travels to the next digestion site, the stomach. There, more enzymes and acid further break down the food you have swallowed. The whole process of digestion is very dependent upon chemical changes. Although physical changes are necessary to break any food into bits, chemical changes help release important energy and nutrients from the food you consume. Chemical changes are the result of *chemical reactions*, that is, the breaking of bonds in one or more substances, and the reforming of new bonds to create new substances.

How do you know when a chemical change has occurred?

You know a chemical change has occurred when one or more starting substances are mixed and you get products that appear to be different from those starting substances. This is because chemical changes involve changes in the chemical bonds that hold substances together. Chemical reactions also involve energy. Therefore, when you see any evidence that energy has been released or absorbed, a chemical change has probably occurred. You can use your powers of observation to determine that a chemical change has taken place. However, sometimes you need to make sure that the chemical properties of the new substances are different from the ones you started with. If you had never seen ice or water before, would you know that they were the same thing?

Try this...

Place a saltine cracker in your mouth. Hold it there for about 10 minutes. Then, how does it taste? Is this evidence of a chemical or physical change?

$+ O_2 = CO_2 + H_2O$

Figure 20.3: *When your body "burns" food for energy, carbon dioxide and water are released. This process is called respiration. You need oxygen for this process to occur. Where do the carbon dioxide and water come from?*

Environmental Issue: Recycling tires

How many tires are thrown away each year?

The next time you travel in a car, think about the tires you are riding on. Did you know that more than 275 million discarded tires are dumped annually into landfills in the United States? Around the world, over 5 million tires are thrown away each day! As the number of cars on the road increases each year, so do the number of tires discarded. For many years, the only alternatives were to throw used tires into landfills, or burn them, which caused air pollution. Today, scientists and engineers are coming up with ways to put a new spin on the discarding of tires. Reusing and recycling scrap tires requires the use of both physical and chemical changes.

What are tires made of?

A typical automobile tire is about 65 percent rubber, 25 percent steel, and 10 percent fiber (plastic). The rubber found in tires is *vulcanized*, or chemically treated to increase the number of sulfur bonds. While this process produces a rigid, strong, and puncture-resistant substance, it also makes it harder to *chemically* break the rubber down into useful substances. Because of this combination of materials, some specialists say that reclaiming the original components from discarded tires is like trying to recycle a cake back to its original ingredients.

How are tires recycled?

Tires can be recycled in two ways: (1) processing them, and (2) using them whole. Whole tire recycling involves using the old tire as is for other purposes, such as landscape borders, playground structures, bumpers, and highway crash barriers. Processing tires for recycling involves chopping them up into pieces, and then separating the rubber and fiber from the steel. While this initial processing is only a *physical change* to the materials found in a tire, it is very challenging because of the way tire manufacturers put the materials together.

An expensive, but very effective way to separate the rubber, fiber, and steel involves cooling the small pieces of tire with liquid nitrogen. This releases the steel, rubber, and fiber pieces from sticking to each other. Next, magnets are used to take out the steel. The pieces of rubber can then be separated from the fiber using density techniques.

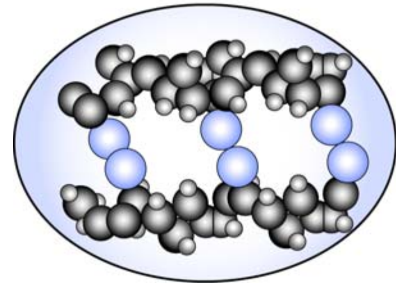


Figure 20.4: *Vulcanized rubber is chemically treated to increase the number of sulfur bonds. This makes the tire harder and more puncture-resistant.*

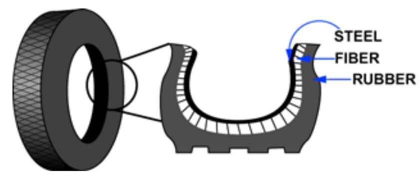


Figure 20.5: *The components of a typical radial tire.*

Use your head...

Based on what you learned in the last unit, can you explain how to separate rubber and fiber using the physical property of density?

Uses for scrap rubber and steel

The small particles of rubber can be used immediately as a substitute for new rubber in products such as footwear, carpet underlay, and waterproofing compounds. It can be mixed with asphalt to make safe and durable road surfaces. In fact, it has been found that adding scrap rubber to the asphalt used to pave roads can significantly decrease braking distances! Asphalt-scrap rubber mixtures are also considered the superior choice for track and field grounds, equestrian tracks, and paved playgrounds.

The steel that is recovered from tires is used to make new steel. In fact, almost everything we make out of steel contains some percentage that is recycled. For nearly as long as steel has been made, recycling has been part of the process.

Recycling 1 ton of steel conserves...
2,500 lbs of iron ore
1,400 lb. of coal
120 lbs of limestone
11 million Btu's of energy

Figure 20.6: *Recycling steel*

Chemically changing rubber

Like plastic, rubber is a polymer. A **polymer** is a molecule that consists of long chains of repeating combinations of atoms. Rubber is a polymer that is very difficult to break down—especially vulcanized rubber. Recent advances in technology have created an environmentally friendly process for breaking the carbon-carbon, carbon-sulfur, and sulfur-sulfur bonds in order to produce smaller molecules. These smaller molecules can be used to make liquid and gaseous fuels, ingredients for other polymers, lubricating oils, and a charcoal that can be used to decontaminate water or soil.

A shortage of discarded tires?

Currently, there are so many uses for discarded tires that a better question seems to be, why not recycle *all* of our discarded tires? Perhaps in the near future, instead of an overabundance of discarded tires, there will be a shortage!

For discussion

1. What are the advantages and disadvantages to whole-tire recycling?
2. Describe the physical changes that are used in processing tires for recycling.
3. What are the advantages and disadvantages to chemically changing scrap rubber?
4. How do you think technological advances in tires could present additional challenges to the recycling process?

Exploring further...

- Interview someone from a company that makes asphalt about using scrap rubber from tires.
- Research further about using recycled tires as a fuel source.
- Find out what happens to discarded tires in your community.

20.2 Chemical Equations

All of the chemical changes you observed in the last Investigation were the result of chemical reactions. A chemical reaction involves breaking the chemical bonds in one or more reactants and reforming chemical bonds into one or more products. All chemical reactions involve breaking and/or forming chemical bonds and all involve energy.

What happens during a chemical reaction?

Did a chemical change take place? In the last Investigation, you observed several chemical reactions. For example, in one of the reactions, you mixed vinegar with baking soda. When you mixed these two substances, you observed a fairly violent bubbling as the baking soda appeared to dissolve into the vinegar. You may have noticed a drop in temperature as the reaction proceeded. These observations provide *evidence* that a chemical change has occurred (Figure 20.7).

Proving chemical change In order to prove that a chemical change has occurred, you need to be able to confirm that the chemical and physical properties of one or more of the products are different from those of the reactants. For example, when methane (natural gas) is burned, it reacts with oxygen to form carbon dioxide and water. This is a common reaction used to heat homes, cook food—or heat up chemistry experiments! Upon careful examination, you would conclude that carbon dioxide has different chemical and physical properties from methane.

Methane + Oxygen ⟶ Carbon Dioxide + Water

Reactants	Products
substances that change	substances that are formed

Where does the new substance come from? In ordinary chemical reactions, atoms are rearranged through the breaking and reforming of chemical bonds. In the methane reaction, the bonds between carbon and hydrogen in methane are broken. Carbon reforms a bond with the oxygen to form carbon dioxide, one of the products. Hydrogen also forms a bond with additional oxygen atoms to produce water. In addition, heat and light are produced.

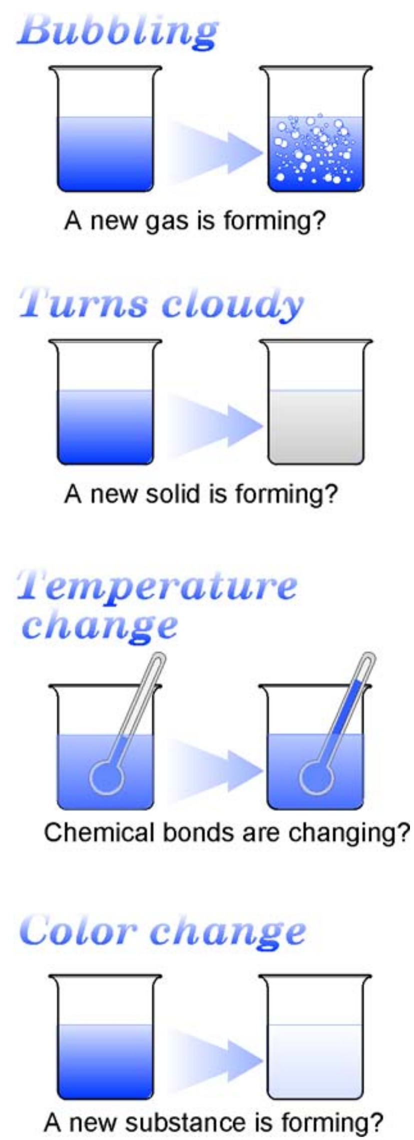


Figure 20.7: *Different kinds of evidence that chemical reactions are occurring.*

How are chemical reactions written?

Chemical reactions as sentences

We could simply write chemical reactions as sentences. For example, we could write the reaction of methane and oxygen as follows:

Methane gas reacts with oxygen gas to produce carbon dioxide and water.

Chemical formulas are more convenient

It is more convenient to use chemical formulas that correspond to the elements and compounds in the reaction. When we use chemical formulas and symbols to represent a reaction instead of using words, it is called a chemical equation.

Remember diatomic molecules?

Do you remember why oxygen is O_2 instead of just O? Recall from the last unit that in nature, most elemental gases do not exist as single atoms (with the exception of the noble gases). Oxygen is called a diatomic molecule, meaning there are two atoms in the molecule. Table 20.1 below shows some of the elements that exist as diatomic molecules.

Using formulas and symbols, the chemical equation for the reaction of methane with oxygen can be written as:

$$CH_4 + O_2 \longrightarrow CO_2 + H_2O$$

Table 20.1: ***Elements that exist as diatomic molecules***

Hydrogen, H_2	Nitrogen, N_2	Oxygen, O_2
Fluorine, F_2	Chlorine, Cl_2	Bromine, Br_2

Chemical equations should show that atoms are conserved in a reaction

The chemical equation above is not completely correct. It does not agree with an important principle in chemistry called conservation of atoms. This principle says that the number of each type of atom on the reactants side of a chemical equation must be equal to the number of each type of atom on the products side of the equation. In other words, you get out of a reaction what you put into it, nothing more, nothing less. If you count the number and type of each atom in the chemical equation above, do they add up on both sides of the equation equally? If you count them carefully, you'll find that the answer is no.

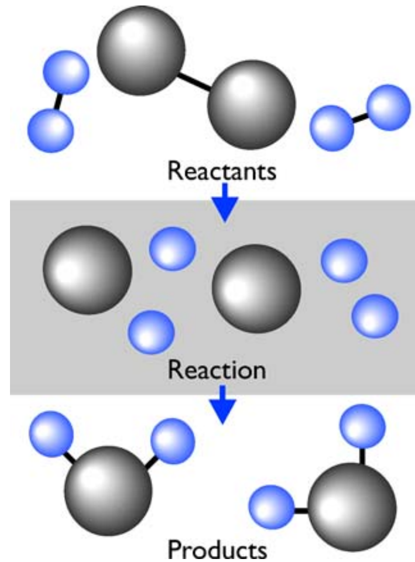


Figure 20.8: *In a chemical reaction, chemical bonds are broken and reformed to make new products.*

substance	chemical formula
methane	CH_4
oxygen	O_2
carbon dioxide	CO_2
water	H_2O

Figure 20.9: *Chemical formulas for substances in the methane reaction.*

How do you write a chemical equation that shows conservation of atoms?

Numbers and types of atoms must balance

Since only whole atoms can react—not fractions of an atom—it is necessary to **balance** the number and type of atoms on the reactants and products sides of the equation. Furthermore, by balancing the numbers and types of atoms, you are not allowed to change the chemical composition of any of the substances on the reactants or products sides. To learn about how to balance chemical equations, let's take another look at that methane reaction.

$$CH_4 + O_2 \longrightarrow CO_2 + H_2O$$

Count the number and type of each atom on both sides of the chemical equation

Once again, count the number of each type of atom on both sides of the reaction. The table below summarizes the numbers:

type of atom	total on reactants side	total on products side	balanced?
C	1	1	yes
H	4	2	no
O	2	3	no

When an equation is unbalanced

The chemical equation is not balanced because the number of hydrogen atoms and oxygen atoms are different on both sides of the equation. To make them equal and balance the equation, you must figure out what number to multiply each compound by in order to make the numbers add up. Remember: You cannot change the number of individual atoms in a compound. That would change its chemical formula and you would have a different compound. You can only change the number of molecules of that compound.

The arrow in the chemical equation is read as:

- "to produce" or
- "to yield"

Subscripts below the symbols for elements tell you how many of each type of atom there are in a molecule.

Figure 20.10: *Helpful hints for reading chemical equations.*

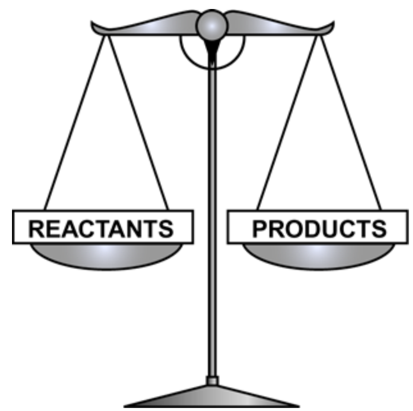
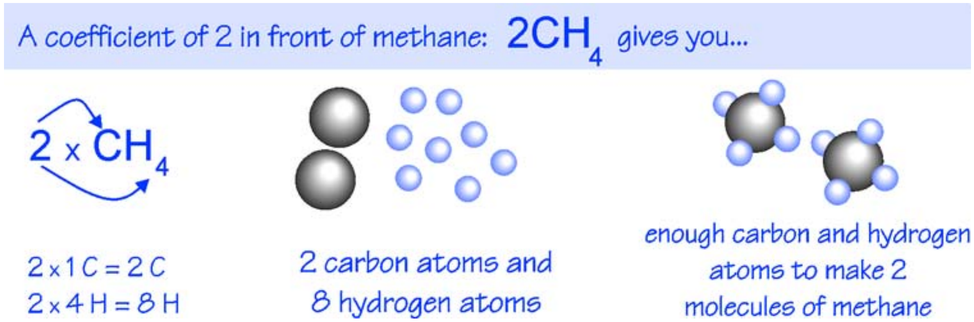


Figure 20.11: *In a chemical equation, the number and type of atoms on both sides of the equation must be equal.*

Balancing equations involves adding coefficients

To change the number of molecules of a compound, you can write a whole number coefficient in front of the chemical formula. When you do this, all of the types of atoms in that formula are multiplied by that number. For example:



Multiplying molecules with coefficients

Figuring out where to place coefficients to multiply the numbers of atoms in a chemical formula is largely a process of trial and error. Let's look at the methane reaction after the correct coefficients have been added:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

Counting the atoms on both sides again, we see that the equation is balanced.

atom	total on reactants side	total on products side
C	1	1
H	4	$2 \times 2 = \mathbf{4}$
O	$2 \times 2 = \mathbf{4}$	$2 + (2 \times 1) = \mathbf{4}$

How do you read a balanced equation?

The balanced equation above can be read as follows:

One molecule of methane reacts with two molecules of oxygen

to produce

one molecule of carbon dioxide and two molecules of water.

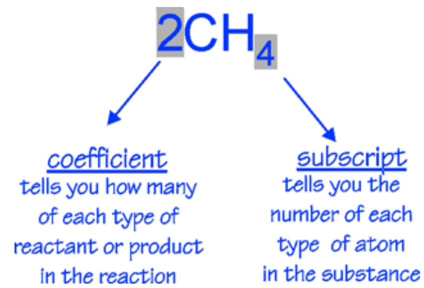


Figure 20.12: *What do coefficients and subscripts mean?*

1. Make sure you have written the correct chemical formula for each reactant and product.
2. The subscripts in the chemical formulas of the reactants and products cannot be changed during the process of balancing the equation. Changing the subscripts will change the chemical makeup of the compounds.
3. Numbers called coefficients are placed in front of the formulas to make the number of atoms on each side of the equation equal.

Figure 20.13: *Things to remember when balancing chemical equations.*

Example: Balancing a common reaction

What happens when you take an antacid?

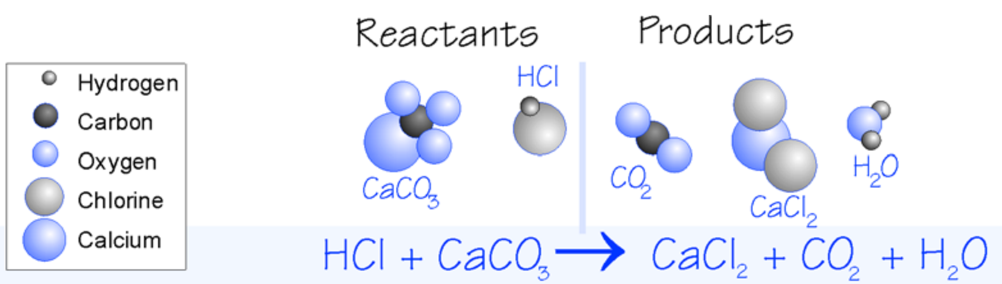
Hydrochloric acid is a substance your stomach normally produces to help you break down food. Sometimes, if you eat spicy foods or worry excessively about studying chemistry, your stomach produces too much hydrochloric acid and you get acid indigestion. Most people take antacids to relieve this painful condition. Many antacids contain calcium carbonate which neutralizes the hydrochloric acid. The products formed are calcium chloride, carbon dioxide, and water. How do you write and balance the chemical equation for this reaction? The following steps outline this process for you:

1. Write the word form of the equation.

Hydrochloric acid reacts with calcium carbonate to produce calcium chloride, carbon dioxide, and water.

2. Write the chemical equation

Consult an ion chart for some of the chemical formulas. The ion chart on page 343 is useful for solving problems of this type. You need to get the chemical formula for each chemical that appears. The chemical equation for this reaction is:



$$HCl + CaCO_3 \rightarrow CaCl_2 + CO_2 + H_2O$$

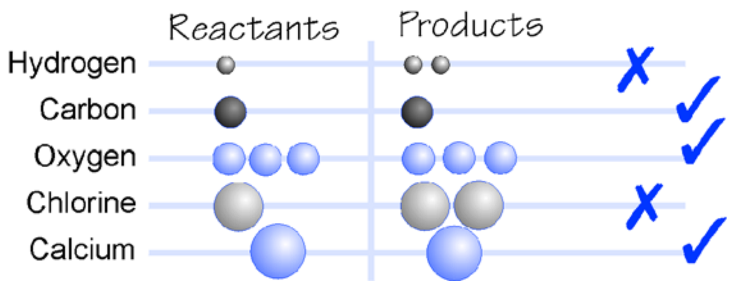
What coefficients mean

- A coefficient placed in front of O_2 means that the reaction will require two oxygen molecules for every methane molecule.
- A coefficient placed in front of H_2O means that two molecules of water will be produced for every one molecule of carbon dioxide.
- No coefficient in front of a chemical formula indicates one molecule.

Figure 20.14: *What is a coefficient?*

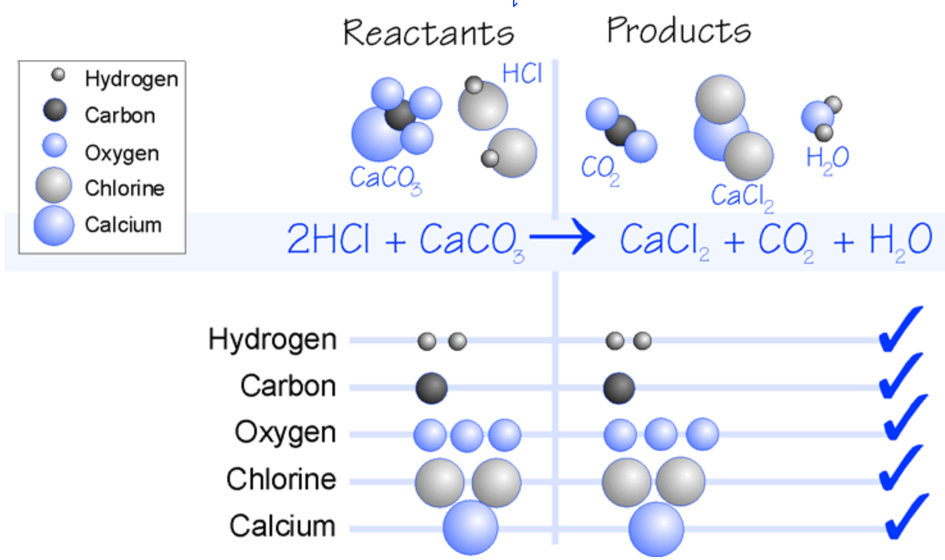
3. Count the number of each type of atom on both sides

The table below summarizes how many atoms of each type are on the reactants' and products' sides of the chemical equation. Notice that there is an extra hydrogen and an extra chlorine on the products' side. These two extra atoms have to come from somewhere. We need to add something to the reactants that will give us an extra chlorine and hydrogen.



4. Add coefficients to balance the equation

Fortunately, one of the reactants is HCl so we can add one more molecule of HCl to the reactants side. In the equation we put a '2' in front of the HCl to indicate that we need 2 molecules. You cannot change the subscripts. In this case, you just need to put a coefficient of 2 in front of HCl to balance the equation.



hydrochloric acid	HCl
calcium carbonate	$CaCO_3$
calcium chloride	$CaCl_2$
carbon dioxide	CO_2
water	H_2O

Figure 20.15: *Chemical formulas for each compound in the reaction.*

atom	reactants	products
H	$1 \times 2 = \mathbf{2}$	2
Cl	$1 \times 2 = \mathbf{2}$	2
Ca	1	1
C	1	1
O	3	3

Figure 20.16: *Is the equation balanced after adding a coefficient of 2 in front of HCl?*

20.3 Conservation of Mass

Have you ever been to a campfire? What happens to the pile of wood after it is finished burning? Of course, it is reduced to a pile of ashes. What happened to the wood? Did it just disappear into the atmosphere? The burning of wood is a chemical reaction. So far, you have learned that every atom in a chemical reaction is accounted for. If this is so, what happened to the mass of the wood in that pile? In this section, you will learn why the mass of the reactants is equal to the mass of the products in any chemical reaction.

Conservation of mass

What is the law of conservation of mass?

In the eighteenth century, chemical reactions were still a bit of a mystery. A French scientist, Antoine Laurent Lavoisier (1743-94), established an important principal based on his experiments with chemical reactions. He stated that the total mass of the products of a reaction is equal to the total mass of the reactants. This statement is known as the law of conservation of mass. Lavoisier's law of conservation was not obvious to many other scientists of the time.

How can you prove the law of conservation of mass?

You already know that when wood is burned, a chemical reaction is taking place, but do you know what happens to the mass of the wood after it has burned? By now, you also know that much of the mass of the burning wood is converted into a gas such as carbon dioxide. This gas then escapes into the atmosphere. How can you prove that the mass of the reactants is equal to the mass of the products in the reaction of burning wood? Lavoisier showed that a *"closed" system* must be used when studying chemical reactions. When chemicals are reacted in a closed container, you can show that the mass before and after the reaction is the same.

An example of how mass is conserved in a reaction

In one of his experiments, Lavoisier placed 10.0 grams of mercury (II) oxide into a sealed container. He heated the container so that the mercury (II) oxide reacted to produce oxygen and mercury. As he observed the reaction, the white, powdery mercury (II) oxide bubbled, and turned into a smaller amount of a silvery liquid. In the reaction, 10.0 grams of mercury (II) oxide reacted in the presence of heat to produce 0.7 grams of oxygen gas and 9.3 grams of mercury. How does this data prove the law of conservation of mass?

Antoine Lavoisier

Born in 1743, Antoine Lavoisier was one of the best known French scientists of his time, and an important government official. As a student he stated "I am young and avid for glory." He demonstrated with careful measurements that it was not possible to change water into soil, but that the sediment observed from boiling water came from the container. He also burned sulfur in air and proved that the products of the reaction weighed more than the reactants and that the weight gained came from the air. Despite his contributions to chemistry, he believed that the existence of atoms was philosophically impossible. He became suspicious to leaders of the French Revolution and was beheaded in 1794.

Conservation and petroleum

Why are we in danger of running out of natural resources like petroleum?

In a chemical reaction, *atoms* are conserved, not necessarily molecules. Petroleum is a mixture of many different molecules. Furthermore, the rate of production of these molecules in nature is very small compared to the rate at which we use them. The United States uses many millions of barrels of petroleum each day in a variety of different chemical reactions. Since the mass of petroleum on earth is limited, how long do you think it will take before we run out?

What is petroleum?

Petroleum is our most important *nonrenewable* resource. From it we obtain fuels to burn in our cars, homes and power plants. It also provides us with the chemicals used to manufacture many different products we use every day. Petroleum is a mixture containing hundreds of different compounds, called *hydrocarbons*, that have two important chemical properties. First, when these compounds burn in oxygen, they release large amounts of energy. Second, molecules of these compounds can be modified in a variety of ways to produce useful materials such as plastics, drugs, explosives and even perfumes! It is no wonder that petroleum is often called "black gold."

What are hydrocarbons?

Hydrocarbons are compounds that consist of many carbon atoms bonded together to form a backbone know as a *carbon chain*. Hydrogen atoms are attached to this chain (Figure 20.17). Do you see where the name "hydrocarbon" comes from? The chemical formulas for some of the hydrocarbons found in petroleum are given in Figure 20.18.

How was petroleum formed?

The formation of petroleum is a chemical reaction that takes millions of years to complete. Many scientists believe that the petroleum we use today originated from animals and plants that lived in the ocean millions of years ago. As these organisms died, they settled to the bottom and were covered with sediments. The plant and animal material was digested by microscopic organisms and, as more sediments piled up on top of them, pressure and heat converted the organic material into petroleum that is now trapped in porous rocks, deep under the earth. While it is likely that petroleum is continuously being formed, its rate of formation is too slow for it to be considered a *renewable* resource.

A short list of petroleum products...

- Aspirin
- Make-up
- Synthetic rubber
- Chewing gum
- Saccharin
- Fibers for clothing
- Artificial flavors
- Fertilizers
- Plastics

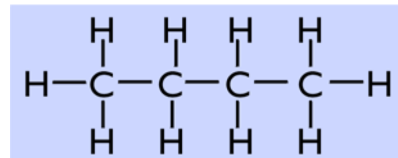


Figure 20.17: *A hydrocarbon*

name	formula
methane	CH_4
ethane	C_2H_6
propane	C_3H_8
butane	C_4H_{10}
pentane	C_5H_{12}
hexane	C_6H_{14}
heptane	C_7H_{16}
octane	C_8H_{18}

Figure 20.18: *Some of the hydrocarbons found in petroleum.*

20.4 Using Equations as Recipes

Have you ever tried to make something from a recipe—say, a chocolate cake—and it didn't turn out quite the way you hoped? Some recipes require you to follow directions and add the correct amounts and types of ingredients. If you left out the eggs, for example, your cake wouldn't turn out at all. A balanced chemical equation is just like a recipe. It tells you the ingredients needed and the amount of each. It also tells you how much of each product will result if the precise amount of reactants are added. In this section, you will learn what chemical equations tell you and how to use them much like you would a recipe for a chocolate cake, although your products won't be as tasty!

Figure 20.19: *What happens when you leave out an ingredient in a recipe?*

What can a chemical equation tell you?

Recipe #1: Chocolate Cake

1 cup flour	1 cup sugar
1/2 cup cocoa powder	1 teaspoon baking powder
1/2 cup butter	1/2 cup milk
1 tsp vanilla	1 egg

In a bowl, combine flour, sugar, cocoa powder, and baking power. Add butter, milk, vanilla, and egg. Mix until smooth. Bake in a 350°F oven for 35 minutes. *Makes 8 servings*

Recipe #2: Water

2 molecules of hydrogen gas
1 molecule of oxygen gas

$$2H_2 + O_2 \longrightarrow 2H_2O$$

Combine the molecules in a closed container. Add a spark of electricity. *Makes two molecules of water.*

Chemical equations are like recipes

How are the two recipes above alike? How are they different? Both recipes give you the ingredients needed, the instructions, and the product that will be produced. Both recipes also give you the *quantities* of ingredients (reactants) needed and the *quantities* of products that are produced.

Recipes tell you the ratios of ingredients

The recipe for chocolate cake shows the *ratios* among the various ingredients needed to make eight servings. If you double the ingredients, you will make twice as many servings. Suppose you only had half a cup of flour. Could you still make eight servings? If you tried it, the cake would probably not turn out like the recipe intended. What would you need to do to make the same final product? Of course, you would use half as much of the rest of the ingredients since you only have half as much flour.

Figure 20.20: *If you had half as much flour, you could only make half the amount of cake.*

Proportional relationships in balanced equations

Just like recipes which show the ratios of the amounts of each ingredient, balanced equations show the ratios of the number of molecules of reactants needed to make a certain number of molecules of products. *The ratios are determined by the coefficients of the balanced equation*. In the formation of water, two molecules of H_2 react with one molecule of O_2 to produce two molecules of H_2O. If you reacted four molecules of H_2 with two molecules of O_2, you would produce four molecules of H_2O instead of two. Doubling the number of each reactant doubles the amount of product formed. What happens if you only double the number of H_2 molecules and not the number of O_2 molecules? How many H_2O molecules could you make? Would you have anything left over? (Figure 20.21)

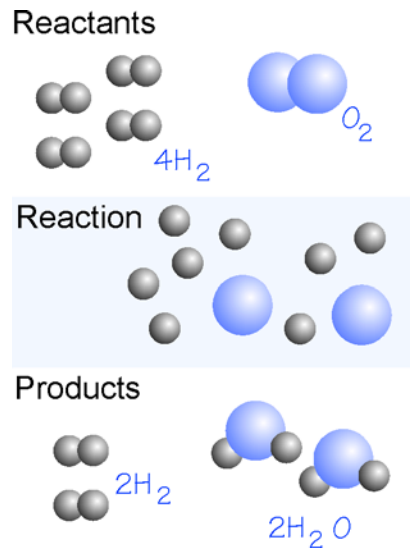
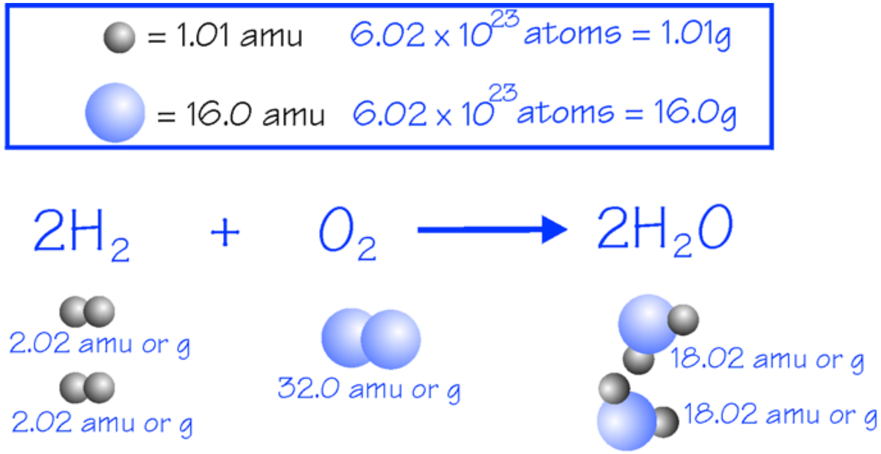


Figure 20.21: *What happens if you double the number of hydrogen molecules in the reaction for the formation of water?*

Balanced equations also show the ratio of relative masses

You have learned that the formula mass of a substance is *relative* to the formula mass of another substance. This is because individual atoms of different elements have an atomic mass relative to the size of their nuclei. Both atomic and formula mass are measured in atomic mass units, or amu. You should also remember that the avogadro number (6.02×10^{23}) of atoms or molecules is equal to the mass of the substance, in grams. For example, the formula mass of water is 18.02 amu. If you had a beaker with 6.02×10^{23} molecules of water, the water would have a mass of 18.02 grams. You have also learned that the coefficients in a balanced equation tell you the ratio of each substance in the equation. If you have a coefficient of 2 in front water in an equation, this means that you have two times the amount of water molecules. Therefore, the molecular mass of water would be 36.04 amu's and 2 x (6.02×10^{23}) molecules would have an actual mass of 36.04 grams.

Let's take a closer look at the formation of water using this logic:



total reactants: 36.04 amu or g = total products: 36.04 amu or g

Balanced equations show how mass and atoms are conserved

As you can see from the balanced equation of the formation of water, there are an equal number of hydrogen and oxygen atoms in the reactants and products. By adding up the atomic masses, you can determine the formula mass in atomic mass units. You can also see that the masses in atomic mass units are equal on both sides of the equation. Therefore, if you have 6.02×10^{23} of each molecule represented in the diagram, a total of 36.04 grams of reactants, will produce 36.04 grams of water—providing all goes as planned. Can you see how a balanced equation can be used like a recipe?

What doesn't a balanced equation tell you?

It is important to note that a balanced equation does not describe the exact conditions under which a reaction will occur. For example, simply putting hydrogen and oxygen molecules together does not always produce water. A jolt of energy will usually result in the formation of water. Many reactions require specific conditions to occur and these are not shown in the balanced equation. Some reactions may not occur at all, even though you can write a balanced equation for them. If this were the case, we could make just about anything we need! Most of the reactions that are used in science and industry are the result of research and experimentation.

Dr. Shirley Ann Jackson

Shirley Ann Jackson grew up in Washington DC in the 1950's and '60's. As a child, she was fascinated with how things work. She and her sister raced go-carts which their Dad helped them build. She spent hours figuring out how to make hers go faster.

Dr. Jackson excelled in her high school classes and won a full scholarship to MIT. She was one of 43 women in her freshman class of 900, and one of 10 African-Americans out of 4,000 undergraduates. Sometimes she felt isolated and lonely. She volunteered in a hospital pediatric ward and tutored children at a local YMCA. This, she says, helped her keep perspective.

In 1973, Dr. Jackson became the first African-American woman to receive a Ph.D. from MIT. Afterward, she researched subatomic particles in government and international labs, and worked on semiconductors and other systems at AT&T Bell laboratories.

In 1995, Dr. Jackson was appointed the Chairman of the U.S. Nuclear Regulatory Commission by President Bill Clinton. She worked to increase nuclear plant safety in the U.S. and with international organizations to enhance worldwide nuclear safety.

Dr. Jackson became president of Rensselaer Polytechnic Institute in 1999. In 2005 she was described by Time Magazine as "Perhaps the ultimate role model for women in science."

What happens if one reactant is used up before another?

If a cookie recipe calls for two eggs and you only have one, can you make a whole batch of cookies? Of course you could only make half as many. The fact that you only have one egg *limits* the amount of cookies you can make. The same is true of chemical reactions. When a chemical reaction occurs, the reactants are not always present in the exact ratio indicated by the balanced equation. In fact, this is rarely the case unless the reaction is performed in a lab with specific amounts of reactants measured. The reaction will run until the reactant that is in short supply is used up.

The reactant that is in short supply is called the limiting reactant

The reactant that is used up first is called the **limiting reactant** because it is used up first and thus, limits the amount of product that can be formed. A reactant that is not completely used up is called an **excess reactant** because some of it will be left over when the reaction is complete.

Because it is used up first, the limiting reactant determines the amount of product formed.

Do reactions always turn out as expected?

Not all reactions turn out exactly as planned. In other words, if you use a specific amount of a limiting reactant and expect the exact amount of product to be formed, you will usually be disappointed. There are many factors involved in the occurrence of reactions that affect the amount of product formed. Usually the amount of product that is formed is less than the amount you would expect. If you can measure the amount of product produced in a reaction, you can determine the percent yield. The **percent yield** is the actual yield divided by the predicted yield and then multiplied by one hundred as in the equation below:

$$\text{percent yield} = \left(\frac{\text{actual yield}}{\text{predicted yield}}\right) \times 100$$

The predicted yield can be determined from the balanced equation for the reaction. The actual yield is determined by simply measuring the mass, in grams, of the product produced in the actual reaction.

Chemistry in industry

When a chemical reaction is carried out by an industry, the more expensive reactant is usually the limiting reactant and the cheaper one is the excess reactant. For example, in the manufacture of artificial flavorings such as vanillin (artificial vanilla) or artificial almond flavoring, acetic acid is reacted with a chemical called an ester to produce the desired flavor. There are many different types of esters that are used, but all of them are more expensive than acetic acid (found in vinegar). Which chemical do you think is used for the limiting reactant?

Chapter 20 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition that will not match any of the terms.

Set One

1. chemical change	a. The type of bonding that an element typically undergoes is an example of this kind of property
2. polymer	b. The state, size, or shape of a substance
3. physical change	c. What happens when two substances react to produce entirely different substances
4. physical property	d. Ice melting is an example of this kind of change
	e. A molecule that consists of long chains of repeating combinations of atoms

Set Three

1. actual yield	a. The reaction that uses carbon dioxide and water to make sugar
2. limiting reactant	b. The amount of product that should be produced in a chemical reaction
3. percent yield	c. The reactant that is in short supply for a chemical reaction
4. predicted yield	d. The numerical relationship between two objects or substances
5. ratio	e. The ratio of actual yield to predicted yield times 100
	f. The amount of product that you can measure after a chemical reaction

Set Two

1. balanced equation	a. The “3” in $CaCO_3$
2. coefficient	b. The “6” in $6H_2O$
3. subscript	c. An equation with an equal number of atoms in the reactants and products
4. Law of conservation of mass	d. The number that represents the number of electrons the atom will lose or gain
	e. You cannot create or lose mass in a reaction

Concept review

1. How can you tell the difference between a physical change and a chemical change?
2. List three examples of a physical change.
3. List three examples of a chemical change.
4. List two differences and two similarities between a recipe for a food item and a chemical reaction.
5. What happens to chemical bonds during a chemical reaction?
6. What is meant by the phrase, "atoms are conserved in chemical reactions"?
7. Describe the contributions of Antoine Laurent Lavoisier to our current knowledge of chemical reactions.
8. Describe three things you can tell from a chemical equation.
9. What is the difference between a limiting reactant and an excess reactant?
10. Give three reasons the actual yield for a product in a reaction is usually lower than the predicted yield.

Problems

1. The process of digestion involves:
   a. Only chemical changes.
   b. Only physical changes.
   c. Both physical and chemical changes.
2. How are ice, liquid water, and water vapor *different* from each other?
   a. Each is a physical state of water.
   b. A chemical change has to occur for ice to become liquid and then for liquid water to become water vapor.
   c. Each of these states of water has a different amount of energy.
3. Which of the following events is *not* evidence that a chemical change has occurred?
   a. When you eat and breathe in oxygen, you have energy and breathe out carbon dioxide.
   b. You mix two solutions and a bright yellow precipitate appears.
   c. You notice that your grandmother's silver is very dark in places and needs polishing.
   d. Your cup of hot chocolate gives off steam.
4. Which of the following events is *not* evidence that a physical change has occurred?
   a. When you accidentally leave a soft contact lens on the bathroom sink overnight, it becomes dry and brittle.
   b. When you mix baking soda and vinegar, the two substances fizz and produce bubbles.
   c. When you take the cap off a soda bottle for the first time, bubbles suddenly appear and rush to the surface of the soda.
   d. Baby food carrots no longer look like carrots because the carrots have been nearly liquefied.

5. Fill out the table for this reaction: $Al + Br_2 \longrightarrow AlBr_3$

type of atom	total on reactants side	total on products side	balanced? (yes or no)
Al			
Br			

6. Which of the following equations is balanced?
   a. $Al + Br_2 \longrightarrow 2AlBr_3$
   b. $2Al + 2Br_2 \longrightarrow 3AlBr_3$
   c. $2Al + 3Br_2 \longrightarrow 2AlBr_3$
   d. $Al + Br_2 \longrightarrow AlBr_3$

7. How would you express the following combustion of ethane, C_2H_6, as a sentence: $2C_2H_6 + 7O_2 \longrightarrow 4CO_2 + 6H_2O$?
   a. Two ethane molecules combine with oxygen to produce carbon dioxide molecules and six water.
   b. Two ethane molecules combine with seven oxygen molecules to produce four carbon dioxide molecules and six water molecules.
   c. Ethane combusts to produce carbon and water.
   d. Four carbon dioxide molecules and six water molecules can be mixed to make oxygen and ethane.

8. Which of the following reactions is balanced?
   a. $CS_2 + 3O_2 \longrightarrow CO_2 + SO_2$
   b. $2N_2O_5 + NO \longrightarrow 4NO_2$
   c. $P_4 + 5O_2 \longrightarrow P_2O_5$
   d. $4Fe + 3O_2 \longrightarrow 2Fe_2O_3$

9. What coefficient for oxygen would balance the equation below?

   $4Fe +$ ____ $O_2 + 6H_2O \longrightarrow 2(Fe_2O_3 \cdot 3H_2O)$

10. Balance the following equations. If an equation is already balanced, say so in your answer.
    a. $Cl_2 + Br \longrightarrow Cl + Br_2$
    b. $CaO + H_2O \longrightarrow Ca(OH)_2$
    c. $Na_2SO_4 + BaCl_2 \longrightarrow BaSO_4 + NaCl$
    d. $ZnS + O_2 \longrightarrow ZnO + SO_2$

11. Balance these chemical equations:
    a. $Cl_2 + KBr \longrightarrow KCl + Br_2$
    b. $NH_3 + O_2 \longrightarrow NO + H_2O$

12. Calculate the formula mass for each of the molecules listed in the *balanced* equation for 11b (above). Hint: Multiply the coefficient for each molecule times the formula mass for the molecule.

    a. NH_3 __________ amu c. NO __________ amu
    b. O_2 __________ amu d. H_2O __________ amu

13. If you had the Avogadro number of each molecule in question 12, what would the masses of these molecules be? Include the coefficient from question 11b in your calculation. Hint: You don't need a calculator for this question!

    a. NH_3 __________ g c. NO __________ g
    b. O_2 __________ g d. H_2O __________ g

14. If oxygen was the limiting reactant in equation 11b and you had only 20 grams of oxygen, what would be the predicted yield of water in this reaction? Be sure to show your work.

15. In the equation to the right, the actual yield of bromide (Br_2) was 19.8 grams when the reaction was performed with 10 grams of chlorine (Cl_2). Calculate the predicted yield for the reaction and then calculate the percent yield.

$$Cl_2\,(g) + KBr \longrightarrow KCl(aq) + Br_2$$

Applying your knowledge

1. List the steps for preparing and eating a salad. Identify which steps have chemical changes and which have physical changes.
2. Identify whether or not a chemical reaction has occurred or will occur in the following situations.
   a. By activating a heat pack, you generate heat to warm your hands.
   b. An orange precipitate forms when two solutions are mixed.
   c. A glass of water turns red when you add dye to it.
   d. The recipe calls for adding sugar and butter to flour.
   e. When you add an effervescent tablet to water, it immediately starts to fizz.
3. Aspirin can be made in the laboratory through a series of reactions. If the actual yield for aspirin was 461.5 grams when the reactions were performed, and the predicted yield was 500 grams, what was the percent yield?
4. The source of fuel in a science lab is methane gas, CH_4, which burns in oxygen gas, O_2, to produce carbon dioxide, CO_2, and water, H_2O. The equation for this reaction is:

   $$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

   If you have ever heated glassware in the lab, you may have noticed a black soot forming on the surface of the glass. This happens when there is insufficient oxygen and not all of the carbon combines with oxygen to form carbon dioxide.
   a. Which element do you think makes up the soot?
   b. Which substance is the limiting reactant in this reaction?
   c. Which substance is the excess reactant?
5. A chocolate sundae is prepared by combining 1/2 cup of ice cream, 2 ounces of chocolate sauce and 1 cherry. Assume you have 10 cups of ice cream, 25 ounces of chocolate sauce and 10 cherries.
   a. What is the maximum number of sundaes you can make?
   b. Which ingredient is the limiting component of the system?
   c. What quantities of the other two "reactants" will be left over when you are finished?
6. Look for situations that demonstrate chemical change. List each situation and describe the evidence of chemical change that you observe. Try to identify the reactants and products.
7. Identify an industry in your community that uses chemical reactions (Actually, it would be more difficult to find one that does not use them!) Examples include: hospitals, sewage or water treatment plants, dry cleaners, photo developers and manufacturers of any product. Research the chemical reactions the facility uses. Write balanced equations for each reaction you identify.

UNIT 7

Changes in Matter

Chapter 21

Types of Reactions

Introduction to Chapter 21

There are many different types of reactions that occur around you all of the time. For example, when you breathe you take in oxygen, which reacts with the sugar in your cells to carbon dioxide and water. It also releases energy for your cells to use or store. This type of reaction is called a combustion reaction. In this chapter you will learn how to classify reactions based on the reactants and products, and whether or not they produce or use energy.

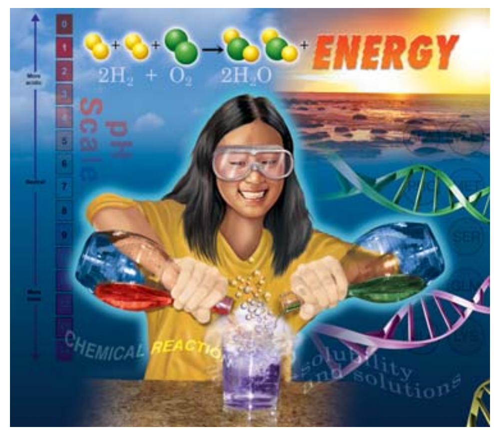
Investigations for Chapter 21

21.1	**Classifying Reactions**	*How can you predict the products in a reaction?*

A double-displacement reaction is a chemical reaction in which the ions from the two reactants change places. One of the new compounds formed is sometimes insoluble and forms a cloudy precipitate. In this Investigation, you will develop a set of rules for precipitate formation that will allow you to make predictions about the types of products in double-displacement reactions.

21.2	**Energy in Reactions**	*How can you classify reactions based on energy?*

You will measure the energy changes in reactions and classify reactions according to how they use or produce energy.



Learning Goals

In this chapter, you will:

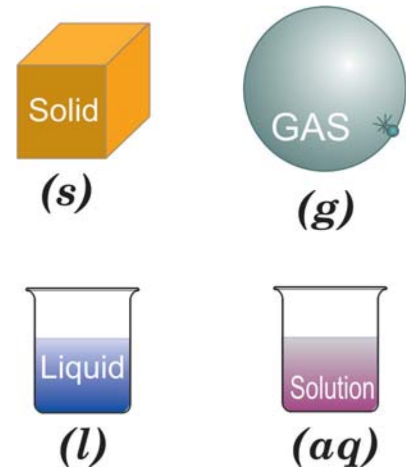
- ✔ Distinguish between different types of reactions.
- ✔ Given the reactants, identify the type of reaction that will occur and predict the products that will be formed.
- ✔ Analyze energy changes that accompany chemical reactions and classify them as exothermic or endothermic.
- ✔ Observe reactions of household chemicals to develop a set of rules for precipitate formation. Use these rules to make predictions.
- ✔ Demonstrate safe practices during laboratory investigations.

Vocabulary

addition reaction	dissolution reaction	exothermic reaction	precipitate
combustion reaction	double-displacement reaction	insoluble	single-displacement reaction
decomposition reaction	endothermic reaction	polymerization	

21.1 Classifying Reactions

Most of the products you use every day are the result of chemical reactions. How do manufacturers know which chemical reactions to use when they make their products? In this section, you will learn how to classify reactions. Being able to recognize the types of reactions will help you predict what types of substances will be produced.



Addition reactions

Compounds are made in addition reactions

In an addition reaction, two or more substances combine to form a new compound. A good example of an addition reaction is the formation of rust:

$$Fe(s) + O_2(g) \longrightarrow Fe_2O_3(s)$$

A general equation for addition reactions is:

$$A + B \longrightarrow AB$$

A and B are elements or compounds, and AB is a compound.

Acid rain

Some fossil fuels, like coal, contain sulfur. When these fuels are burned, the sulfur reacts with oxygen in the air to form sulfur dioxide in the following addition reaction:

$$S(s) + O_2(g) \rightarrow SO_2(g)$$

In air polluted with sulfur dioxide, acid rain is produced in the reaction below:

$$SO_2(g) + H_2O_2(g) \rightarrow H_2SO_4(aq)$$

H_2O_2 is hydrogen peroxide, a substance that is produced in clouds in a reaction between oxygen and water.

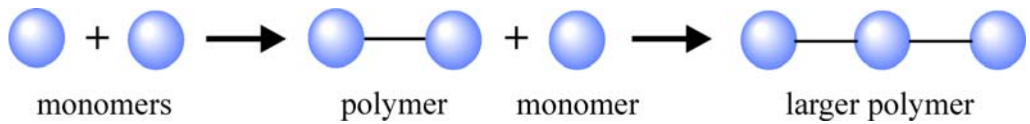
Figure 21.1 explains the meaning of the symbols in parenthesis.

symbol	meaning
(s)	substance is a solid
(l)	substance is a liquid
(g)	substance is a gas
(aq)	substance is dissolved in solution (aqueous)

Figure 21.1: *What do the symbols shown in parentheses mean in equations?*

Polymerization is an addition reaction

In the last chapter, you learned that polymers are large molecules made up of repeating segments. **Polymerization**, or the formation of polymers, is a series of addition reactions taking place to produce a very large molecule. Polymers are made by joining smaller molecules called monomers.



polymer	products
polystyrene	foam containers
polyethylene	food packaging
polyester	clothing
polyvinyl chloride	plumbing (PVC pipes)
polyvinyl acetate	chewing gum

Figure 21.2: *Here are some examples of polymers you may find around your house.*

Decomposition reactions

Compounds are broken down in decomposition reactions

A chemical reaction in which a single compound is broken down to produce two or more smaller compounds is called a **decomposition reaction**. The simplest kind of decomposition is the breakdown of a binary compound into its elements, as in the decomposition of water into hydrogen and oxygen with electricity:

$$2H_2O_{(l)} \longrightarrow 2H_{2(g)} + O_{2(g)}$$

Larger compounds can also decompose to produce other compounds, as in the decomposition of baking soda with heat:

$$2NaHCO_{3(s)} \xrightarrow{heat} CO_{2(g)} + Na_2CO_3 + H_2O$$

The general equation for decomposition is:

$$AB \longrightarrow A + B$$

AB is a compound, and A and B are elements or compounds.

Single-displacement reactions

In single displacement reactions, one element replaces another in a compound

In single-displacement reactions, one element replaces a similar element in a compound. For example, if you place an iron nail into a beaker of copper (II) chloride, you will begin to see reddish copper forming on the iron nail. In this reaction, iron *replaces* copper in the solution and the copper *falls out* of the solution as a metal:

$$Fe_{(s)} + CuCl_{2\,(aq)} \longrightarrow FeCl_{2\,(aq)} + Cu_{(s)}$$

Single-displacement reactions can be represented with the general equation:

$$AX + B \longrightarrow BX + A$$

Where AX is a compound, B is an element, BX is a compound, and A is an element.

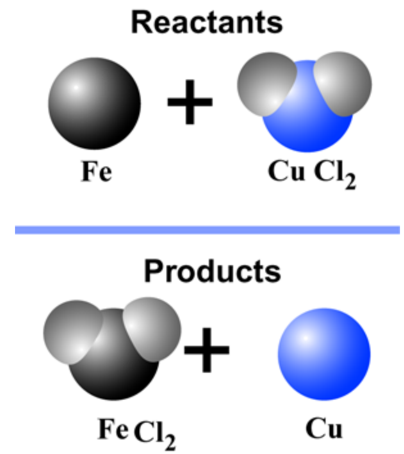


Figure 21.3: *The reaction between iron and copper chloride is a single-displacement reaction.*

Double-displacement reactions

In double-displacement reactions, ions switch places

In double-displacement reactions, ions from two compounds in solution exchange places to produce two new compounds. One of the compounds formed is usually a precipitate that settles out of the solution, a gas that bubbles out of the solution, or a molecular compound such as water. The other compound formed often remains dissolved in the solution.

The general formula for a double-displacement reaction is:

$$AB + CD \longrightarrow AD + CB$$

Where AB and CD are ionic compounds in a solution, and AD and CB are ionic compounds in a solution as well.

What is a precipitate?

The formation of a precipitate occurs when one of the compounds formed in a double-displacement reaction is insoluble, or does not dissolve in water. Precipitates are first recognizable by the cloudy appearance they give to a solution.

Figure 21.4: *The formation of a cloudy precipitate is evidence that a double-displacement reaction has occurred.*

If undisturbed in a beaker, a precipitate will settle to the bottom. Depending on the compound formed, the precipitate can be many different colors from white to fluorescent yellow, as in the reaction between lead (II) nitrate and potassium iodide:

$$Pb(NO_3)_{2(aq)} + 2KI_{(aq)} \longrightarrow PbI_{2(s)} + 2KNO_{3(aq)}$$

Consumer chemistry: Preserving dried fruit

Have you ever opened up a box of dried fruit such as golden raisins or apricots and smelled a slight “sulfur” odor, like a lit match? The odor is caused by *sulfur dioxide*, a gas that is used to preserve the color of dried fruits. This gas is produced in a double-displacement reaction between sodium sulfite and hydrochloric acid:

$$Na_2SO_{3(aq)} + 2HCl_{(aq)} \longrightarrow 2NaCl_{(aq)} + H_2O_{(l)} + SO_{2(g)}$$

The fruit is exposed to the gas, which is absorbed into the skin of the fruit. When you open the box for the first time, some of the gas that has escaped the fruit may not escape your nose!

Combustion reactions

In a combustion reaction, a substance combines with oxygen to release energy

It’s hard to imagine where our society would be without **combustion reactions**. A substance such as wood, natural gas, or propane combines with oxygen, releasing a large amount of energy in the form of light and heat, thus completing a combustion reaction. For example, in the combustion of natural gas to heat a house, methane (natural gas) combines with oxygen to produce carbon dioxide and water:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

the general formula for the combustion of a carbon compound is:

$$\text{Carbon Compound} + O_{2(g)} \longrightarrow CO_{2(g)} + H_2O_{(g)}$$

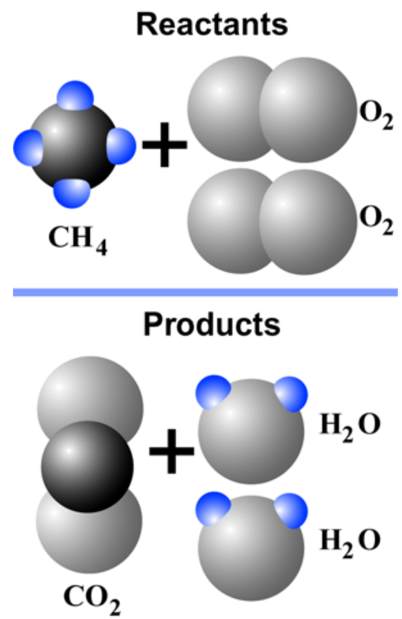


Figure 21.5: *The combustion of meathane gas, in oxygen, produces carbon dioxide and water.*

Energy and the environment: Hydrogen-powered cars

Combustion reactions that do not use carbon compounds as a reactant do not produce carbon dioxide. For example, when hydrogen gas is burned in oxygen, water is the only product:

$$2H_{2(g)} + O_{2(g)} \longrightarrow 2H_2O_{(l)}$$

Perhaps in the future, some of our cars will run by this reaction. In fact, automobile manufacturers are developing hydrogen-powered cars right now using a technology called "fuel cells."

- How would hydrogen-powered cars impact global warming?
- Do some Internet research to find out about fuel cells and hydrogen-powered cars.

Summary of the types of reactions

Table 21.1: ***Summary of the types of reactions***

Type	General equation	Example
addition	$A + B \rightarrow AB$	$2H_2 + O_2 \rightarrow 2H_2O$
decomposition	$AB \rightarrow A + B$	$2NaHCO_3 \rightarrow CO_2 + Na_2CO_3 + H_2O$
single-displacement	$AX + B \rightarrow BX + A$	$Fe + CuCl_2 \rightarrow FeCl_2 + Cu$
double-displacement	$AB + CD \rightarrow AD + CB$	$Pb(NO_3)_2 + 2KI \rightarrow PbI_2 + 2KNO_3$
combustion	carbon compound $+ O_2 \rightarrow CO_2 + H_2O$	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

George Washington Carver

George Washington Carver was born around 1864 in Missouri toward the end of the Civil War. George and his mother, a slave for Moses and Susan Carver, were kidnapped when he was an infant. Only George was found and returned to the Carvers who then raised him. Due to frail health, he spent time exploring nature and developed his talent for studying plants. He pursued plant studies in school and earned an agricultural degree from Iowa State College. He became the first African-American faculty member at the college and earned his master's degree two years later. Soon afterward, Booker T. Washington, founder of Tuskegee Institute in Alabama, contacted Carver to lead the agricultural department. There, Carver taught students and local farmers to rotate crops annually to enrich the soil. Benefits included improving the cotton crop and adding new cash crops such as peanuts and sweet potatoes. Carver is especially known for gathering a list of products and recipes that utilized the peanut plant. His many achievements include research on soy as a possible biofuel, displaying artwork at the 1893 World's Fair, and meeting with three American presidents.

Example: Predicting the products of a reaction

Can you predict the products of this reaction?

Silver becomes tarnished as time passes. Have you ever eaten something with a tarnished fork or spoon? The black tarnish is silver sulfide, the result of a reaction between the silver metal and sulfur in foods. Some products claim to be able to remove the tarnish without destroying the silver. One product contains aluminum metal in a solution. Write the complete reaction for removing tarnish with this product.

1. Write the chemical formulas for the reactants

Silver sulfide reacts with the aluminum metal in the product.

Silver = Ag^+ ion; sulfide = S^{2-} ion

The chemical formula for silver sulfide is Ag_2S

Aluminum is an element so its formula is Al

Chemical formulas for reactants: $Ag_2S + Al$

2. Identify the type of reaction

This is a *single replacement* reaction because of the general formula:

$$AX + B \longrightarrow BX + A$$

3. Predict the products and write their chemical formulas

Ag_2S is a compound and Al is an element so Al will replace Ag.

The products formed will be aluminum sulfide and silver metal.

Aluminum ion = Al^{3+}; sulfide ion = S^{2-}

Chemical formulas for products: $Al_2S_3 + Ag$

4. Write and balance the complete equation

Unbalanced equation:

$Ag_2S + Al \rightarrow Al_2S_3 + Ag$

Balanced equation:

$3Ag_2S + 2Al \rightarrow Al_2S_3 + 6Ag$

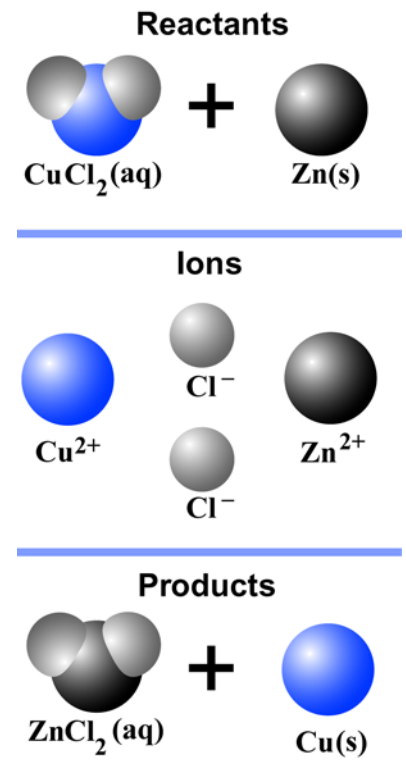


Figure 21.6: *The reaction of copper chloride (in solution) with zinc metal is another example of a single-displacement reaction.*

21.2 Energy in Reactions

You have learned that when most reactions take place, chemical bonds must be broken and new chemical bonds must be formed. Breaking chemical bonds requires energy. When new bonds are formed, energy is released. Why do some reactions *produce* more energy than others? Why do some reactions *use* more energy than they produce? In this section, you will learn about both these types of reactions and some ways we use them in household products.

Exothermic reactions

Exothermic reactions produce energy

In many reactions, less energy is required to break the bonds in the reactants than is released when bonds are formed to make new products. In these types of reactions, called **exothermic reactions**, some type of energy is released. The combustion of gasoline to run automobiles is an exothermic reaction. Some other exothermic reactions happen so slowly that you cannot feel the heat, like the formation of rust. Exothermic reactions can be detected by measuring a rise in temperature.

What are some useful exothermic reactions?

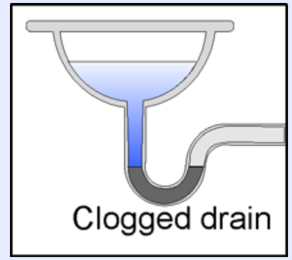
It is fairly obvious that we use exothermic reactions every day to heat our homes, drive our cars, and cook our food. These reactions are all combustion reactions that produce tremendous amounts of heat and light. Some other exothermic reactions may not be so obvious.

Meals ready to eat

The US Army developed a Meal, Ready to Eat (or MRE) for the 1991 Gulf War. These meals have a special sleeve placed around the food, which is wrapped in aluminum foil. When water is added to the sleeve, the resulting chemical reaction produces enough heat to cook the food inside the foil. What's in that sleeve? It is a pad that contains suspended particles of magnesium metal. When the magnesium reacts with the water to produce magnesium hydroxide, heat is released. The heat is conducted through the aluminum to heat the food. The result is a piping hot meal, ready to eat!

$$Mg_{(s)} + 2H_2O_{(l)} \rightarrow Mg(OH)_{2(aq)} + H_{2(g)}$$

Clogged drain?



Many drain cleaners are a mixture of sodium hydroxide and aluminum filings. When these two substances mix in water, they react to produce enough heat to melt the fat in your clogged drain. The bubbles produced are hydrogen gas.

Can you write the balanced equation for this reaction?

Endothermic reactions

How does a cold pack work?

Have you ever used an "instant cold pack" as a treatment for aching muscles? These products, found in your local drugstore, use a special chemical reaction that has to do with energy. The product usually comes in a plastic bag. Inside of the bag is a packet of water surrounded by crystals of ammonium nitrate. To activate the cold pack, you squeeze the plastic bag to release the water. When the water contacts the ammonium nitrate crystals, a reaction occurs and the pack becomes icy cold.

$$NH_4NO_3(s) + H_2O(l) \rightarrow NH_4^+(aq) + NO_3^-(aq)$$

The reaction gets very cold because it takes energy to dissolve the ionic bonds in the ammonium nitrate.

Endothermic reactions require more energy than they produce

Sometimes more energy is required to break the bonds in the reactants than is released from the formation of new bonds in the products. In these reactions, called **endothermic reactions**, more energy must be provided for the reaction to take place than is released. You can detect an endothermic reaction by measuring a decrease in the temperature. The cold pack reaction can be classified as an endothermic reaction.

Look at the cold pack reaction in above. Besides being endothermic, this reaction is also called a dissolution reaction. A **dissolution reaction** occurs when an ionic compound dissolves in water to make an ionic solution.

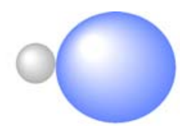
What are some useful endothermic reactions?

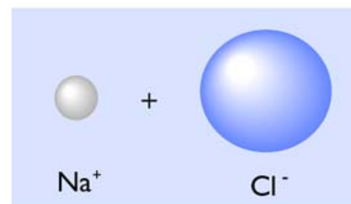
Most of the reactions used in industry to produce useful materials and products require more energy than they produce. This is one of the reasons sources of energy are so important to industry. For example, the refining of ores to produce useful metals frequently uses an endothermic reaction, as in the refinement of aluminum ore:

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

This reaction requires the input of energy because it takes more energy to break the bonds in the aluminum oxide than is released when the products are formed.

Figure 21.7: *An instant cold pack contains ammonium nitrate crystals and a packet of water. When squeezed, the water is released and the reaction occurs.*





NaCl in water

Figure 21.8: *When NaCl is in water, it dissolves into positive and negative ions. This is an example of a dissolution reaction.*

Chapter 21 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition that will not match any of the terms.

Set One	
1. combustion reaction	a. A large molecule with repeating units of smaller molecules
2. decomposition reaction	b. A molecule that is used to speed up reactions
3. double-displacement reaction	c. The process of attaching small molecule units together to make a large molecule
4. polymer	d. $AB \longrightarrow A + B$
5. polymerization	e. $AB + CD \longrightarrow AD + CB$
	f. A reaction that is used to obtain energy from fuel

Set Two	
1. precipitate	a. A reaction that uses more energy than it produces
2. single-displacement reaction	b. $AB + CD \longrightarrow AD + CB$
3. endothermic reaction	c. $A + B \longrightarrow AB$
4. addition reaction	d. $AX + B \longrightarrow BX + A$
5. exothermic reaction	e. The insoluble product of a double-displacement reaction
	f. A reaction that produces more energy than it uses

Concept review

1. Are combustion reactions usually exothermic or endothermic?
2. The formation of rust is represented by the following reaction:

   $4Fe(s) + 3O_2(g) \longrightarrow 2Fe_2O_3(s) + \text{energy}$

   a. Classify this reaction as either: single-displacement, decomposition, addition, combustion or double-displacement.
   b. Is this reaction exothermic or endothermic?
3. What conditions must be met in order for a reaction to be considered exothermic?
4. A reaction that requires more energy to break the bonds in the reactants than is released when new bonds are formed in the products is a(n):
   a. MRE reaction.
   b. endothermic reaction.
   c. silver reaction.
   d. exothermic reaction.

Problems

1. Identify the following reactions as: addition, decomposition, single-displacement, double-displacement, or combustion reactions.
   a. $NaS (aq) + ZnNO_3(aq) \longrightarrow NaNO_3(aq) + ZnS (s)$
   b. $6Li(s) + N_2 \longrightarrow 2Li_3N$
   c. $2KClO_3 \longrightarrow 2KCl + 3O_2$
   d. $2C_3H_7OH + 9O_2 \longrightarrow 6CO_2 + 8H_2O$
   e. $Mg + 2AgNO_3 \longrightarrow Mg(NO_3)_2 + 2Ag$
2. Complete the reactions below. You are not required to balance this set.
   a. $H_2SO_4(aq) + BaCl(aq) \longrightarrow$
   b. $ZnSO_4(aq) + Na_3PO_4(aq) \longrightarrow$
   c. $HCl (aq) + K_2SO_3 \longrightarrow$
   d. $SnCl_2 + Fe_2(SO_4)_3 \longrightarrow$
3. Use the solubility rules to identify the precipitate, if any, for each reaction in question 2.
4. Complete the following reactions by predicting the products. Then, balance each equation.
   a. $Fe(s) + CuCl_2(aq) \longrightarrow$
   b. $C_2H_6(g) + O_2(g) \longrightarrow$
   c. $NaCl(aq) + NH_4OH(aq) \longrightarrow$
   d. $H_2O \longrightarrow$
   e. $Cu(s) + O_2(g) \longrightarrow$
   f. $Al_2O_3 \longrightarrow$
   g. $Mg(s) + HCl(aq) \longrightarrow$
   h. $LiNO_3(aq) + MgCl_2(aq) \longrightarrow$

Applying your knowledge

1. Many drain cleaners are a mixture of sodium hydroxide and aluminum filings. When these two substances mix in water, they react to produce enough heat to melt the fat in a clogged drain. The bubbles produced are hydrogen gas. The complete reaction occurs in two steps:

   step 1: $Al(s) + NaOH(aq) \rightarrow Al(OH)_3(s) + Na^+ (aq)$

   step 2: $Na^+(aq) + H_2O \rightarrow Na_2O(s) + H_2(g)$

   a. Classify step 1 of the reaction as: addition, single-displacement, double-displacement or decomposition.
   b. Is this an endothermic or an exothermic reaction?
   c. Balance each equation for each step of the reaction.
2. Propane, C_3H_8, is a gas that is used by cooks and campers every day. It is burned in oxygen in order to cook food, provide heat and light, and even to run refrigerators in areas that do not have electricity. Write the complete, balanced equation for the combustion of propane.
3. Light bulb filaments are made of the element tungsten. When this metal is heated, it usually forms an oxide with the oxygen in the air. This causes the metal to become brittle and fall apart. Can you explain why the filament of tungsten inside of a light bulb does not form an oxide? (Hint: think about the structure of a light bulb.)

UNIT 7

Changes in Matter

Chapter 22

Chemistry and the Environment

Introduction to Chapter 22

The reactions of elements and compounds are everywhere in the environment. In fact, the Earth's environment as we know it is the result of the reactions of organisms. Plants, for example, produce the atmospheric oxygen that we depend on. In this chapter you will learn about how nuclear reactions in the sun produce the energy that eventually leads to this oxygen production. As you learn more about nuclear and carbon reactions, you will see the role they play in improving and affecting our environment and lifestyles.

Investigations for Chapter 22

22.1	**Nuclear Reactions**	*How do you simulate nuclear decay?*

With 92 protons and 146 neutrons, the nucleus of uranium-238 has a tendency to fall apart or "decay." It emits radiation in the forms of particles and energy until it becomes an atom with a more stable nucleus. The entire radioactive decay process for uranium-238 takes about 5 billion years! In this Investigation, you will simulate the radioactive decay of an element.

22.2	**Carbon Reactions**	*How do your choices impact the environment?*

If you needed to buy a car to drive to school or work, what would you buy? How would you make your decision? In this Investigation, you will use consumer information to evaluate how your decision affects the environment and your personal finances. You will calculate how much carbon dioxide your car or truck would produce. In the last part of the Investigation, you will see how the sun's energy may be used to reduce carbon dioxide in the atmosphere.

Learning Goals

In this chapter, you will:

- ✔ Compare and contrast nuclear reactions with chemical reactions.
- ✔ Describe the environmental impact of nuclear reactions.
- ✔ Research and describe the environmental and economic impact of the end-products of chemical reactions.
- ✔ Identify how personal choices about products can have an impact on the environment.
- ✔ Evaluate the impact of scientific research on society and the environment.
- ✔ Organize data and use it to predict trends.

Vocabulary

alpha decay	emissions	half-life	radioactive
alpha particles	fission	isotope	radioactive isotope
beta decay	fossil fuels	nuclear reactions	stable
beta particles	fusion	nucleons	unstable
carbon dating	global warming	photosynthesis	

22.1 Nuclear Reactions

In the Middle Ages, individuals called alchemists spent a lot of time trying to make gold. Often, they fooled people into believing that they had made gold. Although alchemists never succeeded in making gold, their experimental techniques laid the foundation for the field of chemistry.

Gold is an element. Is it possible to make an element? What do you think?

Making an element is possible only if you can achieve a nuclear reaction, something the alchemists could not do. Nuclear reactions involve either combining or splitting the nuclei of atoms. In this section, you will learn about nuclear reactions as well as nuclear energy and radioactivity.

Figure 22.1: *Gold is a precious metal. In the Middle Ages "alchemists" tried to turn ordinary substances into gold. Using the means they had at the time, alchemists never succeeded in making gold. Today it is possible, but not economically reasonable to make gold!*

Making gold is not a simple task

Gold on the periodic table

Do you know where to find gold on the periodic table? Unlike what you might expect, its symbol is not Gd, nor Go, or Ga. The symbol comes from the Latin word ***aurum***. The Romans used this word to refer to gold, but it also meant "shining dawn."

Atoms are distinguished by number of protons

Although gold's ancient name is descriptive, an atom of gold is defined by its atomic number, 79. This number identifies how many protons an atom has in its nucleus. All atoms that have 79 protons are gold atoms. Atoms with one more proton are mercury (Hg) atoms, and atoms with one fewer proton are platinum (Pt) atoms. In these terms, it seems that it would be easy to make gold. You could simply combine nuclei (the plural form of nucleus) of different atoms until you made an atom with 79 protons. Which atoms do you think could be combined to make gold?

Fusion and fission reactions provide a way to make gold

To make gold, you would need to perform a nuclear reaction. There are two kinds of nuclear reaction: fusion and fission. The process of combining the nuclei of atoms to make different atoms is called fusion. To make gold, you could also split the nucleus of an atom that has more protons and neutrons than gold. Breaking up the nucleus of an atom is called fission. Scientists can use a special machine called a particle accelerator to bombard particles and atoms in order to achieve fusion and fission reactions. However, only a very small number of atoms can be made in this way at one time.

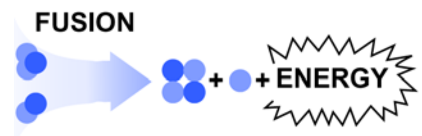
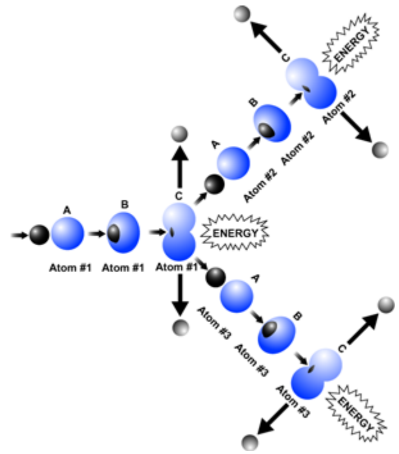


Figure 22.2: *In fusion, nuclei are "fused," a particle is emitted, and a lot of energy is released. The reaction shown above shows the fusion of hydrogen-3 (1 proton + 2 neutrons) with hydrogen-2 (1 proton + 1 neutron) to make a helium nucleus, a neutron and energy. In the graphic, the dark blue dots are protons; the lighter blue dots are neutrons.*

What is a nuclear reaction?

What are nuclear reactions?

Fission and fusion are **nuclear reactions**. Protons and neutrons—the two most important subatomic particles in the nucleus—participate in these reactions. Collectively, the protons and neutrons in the nucleus are called **nucleons**. Nuclear fission can be started when a neutron (dark ball) bombards a nucleus (blue ball). A chain reaction results. A free neutron (step A) bombards a nucleus (step B) and the nucleus splits releasing more neutrons (step C). These neutrons then bombard other nuclei.



Chemical vs. nuclear reactions

Chemical reactions involve only the outermost electrons of atoms. A summary of the differences between chemical and nuclear reactions is listed in the table below.

	chemical reactions	nuclear reactions
What part of the atom is involved?	Outermost electrons	Protons and neutrons in the nucleus
How is the reaction started?	Atoms are brought close together with high temperature or pressure, or catalysts, or by increasing concentrations of reactants	High temperature is required or atoms are bombarded with high-speed particles
What is the outcome of the reaction?	Atoms form ionic or covalent bonds	The number of protons and neutrons in an atom usually changes
How much energy is absorbed or released?	A small amount	A huge amount
What are some examples?	Burning fossil fuels, digesting food, housecleaning, making medicines and commercial products	Nuclear energy, taking x-rays, treating cancer, irradiating food to sterilize it, the sun generating heat and light

Chien-Shiung Wu

During World War II, Chinese-American physicist Chien-Shiung Wu played an important role in the Manhattan Project, the army's secret work to develop the atomic bomb. In 1957, she overthrew what was considered to be an indisputable law of physics, changing the way we understand the weak nuclear force.

Chien-Shiung Wu was born in 1912 near Shanghai, China. She attended a boarding high school that had two sections—a teacher training school and an academic school. Wu enrolled in the teacher training area. She graduated first in her class and was invited to attend a prestigious university in Nanjing. After earning a physics degree, Wu emigrated to the United States. She earned a Ph.D. from the University of California-Berkeley in 1940.

After working on the Manhattan Project, Wu continued research in nuclear physics at Columbia University. She won the National Medal of Science, the nation's highest award for scientific achievement, in 1975.

Forces in the nucleus

Opposites attract to form neutral atoms

Protons are positively charged particles. Consider an atom like boron with an atomic number of 5. The nucleus of a boron atom has five positively charged protons. What keeps these positive particles packed together? If “likes repel,” shouldn’t the protons fly apart from each other?

Strong nuclear force is the key

The nucleus stays together because of the *strong nuclear force*. The strong nuclear force attracts every proton and neutron to every other proton and neutron. The attractive forces from the neutrons and protons together are stronger than the electromagnetic force that cause the protons to repel each other.

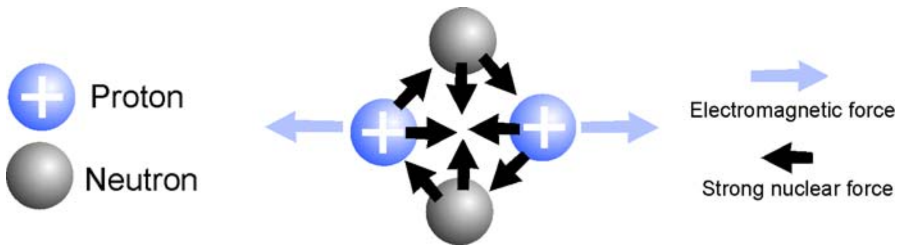


Figure 22.3: *Theoretical physicist, Hideki Yukawa (1907-1981) was the first Japanese to receive a Nobel Prize. He won the award in 1949 for his theory of strong nuclear force. This theory predicted the meson, a elementary particle that was later discovered.*

The importance of neutrons

For every atom heavier than helium there needs to be at least as many neutrons as protons to hold the nucleus together. For example, calcium-40 has 20 protons and 20 neutrons. For heavier atoms, more neutrons are needed than protons. This is because neutrons add attractive force without electromagnetic repulsion. For atoms with more than 83 protons, even the added strong nuclear force from neutrons is not enough to hold the nucleus together. Every nucleus with more than 83 protons is unstable.

Different atoms of an element can have different numbers of neutrons

You may already know that the atoms in an element can have different numbers of neutrons. For example, all carbon atoms have six protons, but some have six neutrons and some have seven neutrons. Atoms of the same element that differ in their number of neutrons are called **isotopes**. The best way to identify isotopes is by their atomic mass number. A carbon atom with six neutrons is referred to as carbon-12 and one with seven neutrons is carbon-13. The *atomic mass number* of an isotope is the number of protons plus the number of neutrons in an atom.

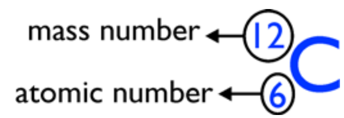


Figure 22.4: *The isotopes of carbon can written with the mass number above the atomic number. Here, we will call this format the “isotope notation.” The diagram above is for carbon-12, one of the common and stable isotopes of carbon.*

What is radioactivity?

An unstable nucleus is radioactive

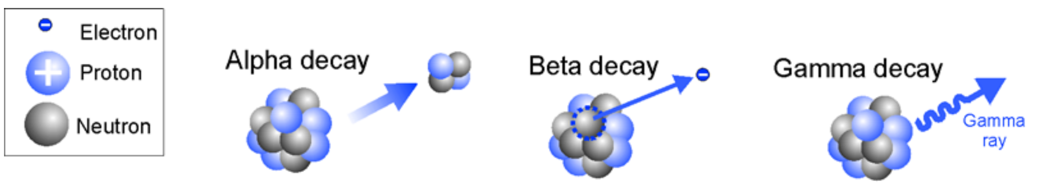
Radioactivity is how we describe any process where the nucleus emits particles or energy. The nucleus of a uranium-238 atom is radioactive. It emits radiation in the forms of particles and energy as it transforms itself into an atom with a more stable nucleus. In Figure 22.5, uranium-238 emits two protons and two neutrons to become a thorium-234 atom. Eventually, uranium-238 decays naturally to lead-206, which is not radioactive. The entire decay process takes about 5 billion years!

The three kinds of nuclear decay

Unstable isotopes emit three kinds of radioactive decay. These include alpha particles, beta particles, and gamma rays.

Alpha decay

In alpha decay, a particle that has two protons and two neutrons is released from an unstable nucleus. This particle is called an alpha particle. When a radioactive isotope undergoes alpha decay, it ejects an alpha particle. Uranium-238 undergoes alpha decay to become thorium-234 (Figure 22.5).



	Alpha decay	Beta decay	Gamma decay
Protons	Decrease by 2	Increase by 1	Unchanged
Neutrons	Decrease by 2	Decrease by 1	Unchanged

Beta decay

Beta decay occurs when a neutron in the nucleus of a radioactive isotope splits into a proton and an electron. The proton stays behind in the nucleus, but the electron is emitted. The electron is called a beta particle. Carbon-14 (a radioactive form of carbon) undergoes beta decay to become nitrogen-14. Why are the atomic masses of the carbon and nitrogen atoms both 14?

Gamma decay

Gamma decay involves the release of high-energy, electromagnetic radiation from the nucleus of an atom. Gamma rays have shorter wavelength than X rays and have much more energy.

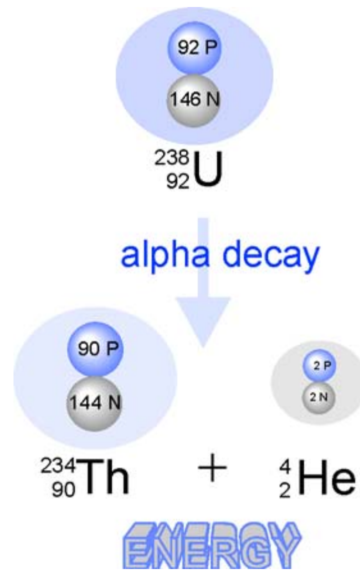


Figure 22.5: *When uranium-238 undergoes alpha decay, it becomes thorium-234 and releases a helium nucleus. Additionally, a lot of energy is released. The helium nucleus is called an alpha particle. The mass number for the elements on one side of the equation above equal the mass numbers on the other side. Nuclear reactions follow the law of conservation of mass.*

Use your head...

Gold-185 decays to iridium-181. Is this an example of alpha or beta decay?

Using nuclear reactions for our energy needs

Sun power is nuclear power

Nuclear reactions are more common in everyday life than you might think. For example, consider that we all depend on the energy from the sun. We need the sun to warm us. What we and other animals eat depends on plants and algae converting energy from the sun into food. Even the fuel we use in our cars, derived from the fossil remains of plants and animals, can be attributed to the sun's energy. The huge amount of energy produced in the sun is the result of a multi-step fusion reaction in which hydrogen isotopes are forced together in the extremely hot interior of the sun to make helium.

Nuclear reactors

Some of our energy production on Earth involves nuclear reactors that use fission to produce heat. This heat is then used to generate steam for running turbines. In turn, the turbines generate electricity for homes and businesses.

Nuclear reactors produce hazardous nuclear waste

Almost all of our energy technologies also produce some harmful waste products. Burning coal and oil creates waste gasses that contribute to global warming and acid rain. Although nuclear reactors do not normally produce harmful emissions, they do produce nuclear waste. What is nuclear waste and why is it a problem?

Half-life

To understand nuclear waste, you have to understand the term **half-life**. All radioactive elements have a half-life. This means that there is a certain length of time after which *half* of the radioactive element has decayed. For example, the half-life of carbon-14 (one of the radioactive isotopes of carbon) is 5,730 years. This means that if you start out with 100 atoms of carbon-14, 5,730 years from now only 50 atoms will still be carbon-14. The rest of the carbon will have decayed to nitrogen-14 (a stable isotope). As a radioactive element decays, it emits harmful radiation (alpha and beta particles, and gamma rays). By breaking chemical bonds, radiation can damage cells and DNA. Exposure to radiation is particularly harmful if it is too intense or for too long a period of time.

The half-life of uranium

The radioactive element in nuclear reactor fuel is uranium. When a uranium atom breaks up (fission), giving off energy, the resulting smaller atoms are also radioactive. Many of the atoms which are decay products of uranium fission have long half-lives. That means spent fuel from a reactor stays radioactive for a long time, which is why it is dangerous.

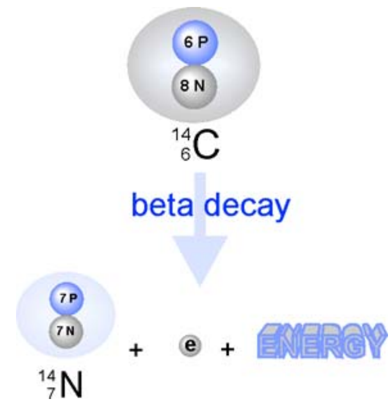


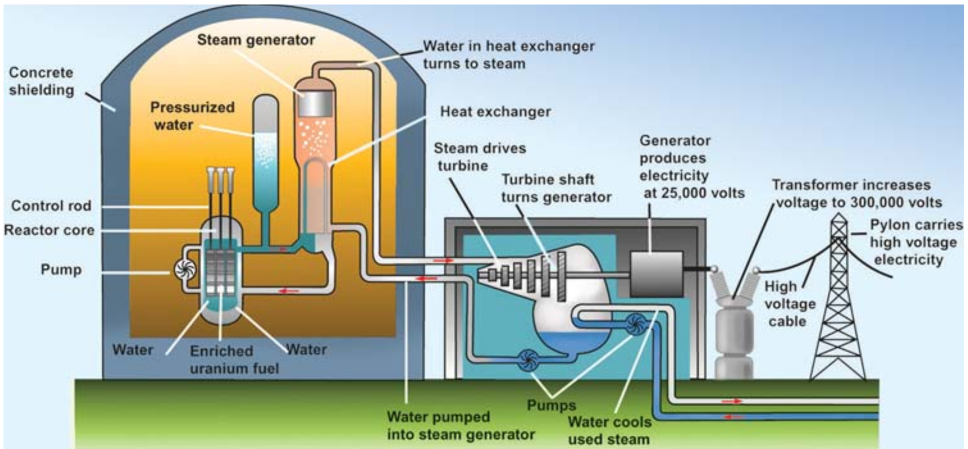
Figure 22.6: *When carbon-14 undergoes beta decay, it becomes nitrogen-14. This is because one of the neutrons in the carbon nucleus becomes a proton and an electron. The proton stays in the nucleus and an electron and energy are emitted.*

Radiation all around

Because you cannot see or feel radiation, you may not be aware that it is all around you. Many common objects contain radioactive isotopes. Exposure to radiation can come from space (radiation entering the Earth's atmosphere), having an x ray, brick or stone buildings, or brazil nuts! Fortunately, exposure to radiation from these sources is very low.

A plan for storing nuclear waste

In 1974, the U.S. Congress established the Nuclear Regulatory Commission (NRC) as a monitoring organization for nuclear fuel use and the storage of nuclear waste. There is a proposed permanent storage facility for highly radioactive nuclear waste that may be built by 2007 in Yucca Mountain, Nevada. Presently, nuclear waste is stored in special facilities around the country in containers meant to last 100 years. Storing nuclear waste is a very controversial issue. What do you think should be done about storing it?



How much energy comes from nuclear reactors?

The US gets about 1/5 (20%) of its energy from nuclear fission reactors. The remaining energy comes from coal, natural gas, oil, and hydroelectric dams. Many foreign countries get more of their electricity from nuclear fission reactors. France is the most dependent on nuclear power. About 75% of electricity generated in France comes from nuclear fission. Sweden and Belgium also get more than 50% of their energy from nuclear fission.

What is nuclear fusion?

Nuclear fission is one of two ways to get energy from the atomic nucleus. The other process is called nuclear fusion. In nuclear fusion, light atoms are heated up to extremely high temperatures so their nuclei can fuse together to create heavier atoms. The process gives off tremendous amounts of energy, and is what powers the Sun and the stars.

Roscoe Koontz

Roscoe Koontz was born in 1922 in St. Louis, Missouri. During World War II, he was chosen to participate in a special Army pre-engineering program at West Virginia State college. After the war, he continued his education at Tennessee State University, where he earned a bachelor's degree in chemistry.

Koontz was invited to participate in the Atomic Energy Health Physics Fellowship Training Program at the University of Rochester in 1948. He became one of the world's first health physicists. A *health physicist* is a professional who makes sure that the risks associated with overexposure to radiation are minimized. The health physicist looks at a situation where ionizing radiation is to be used—a nuclear reactor, x-ray machine, high energy particle accelerator, or medical radiation. When Koontz entered the field, few standards existed to protect workers and the public from harmful radiation. Koontz and others developed many of the strategies currently used in radiation safety.

Using nuclear reactions in medicine and science

Radioactive isotopes can be used to detect problems in systems

Radioactive isotopes (also called *radioisotopes*) are commonly used as tracers in medicine and science. By adding a radioactive isotope into a system (such as the human body or an underground water supply), problems can be detected. The tracer's radiation allows it to be detected using a Geiger counter or other machine and followed as it travels through the system. In the food industry, nuclear reactions are used to sterilize packaged foods.

The age of some fossils can be determined by measuring carbon-14

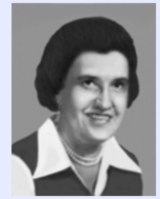
It is possible to figure out the age of objects made from plants or animals that are between 50,000 and a few thousand years old using **carbon dating**. Plants and animals absorb carbon into their tissues. Much of the carbon they absorb is carbon-12 and carbon-13 because these are the most abundant carbon isotopes. However, some carbon-14 is also absorbed. Carbon-14 undergoes radioactive decay and has a half-life of 5,730 years. By measuring the amount of carbon-14 remaining in a plant or animal fossil, the age of the fossil can be estimated if it isn't too old. Why do you think very old fossils cannot be dated using carbon dating?

Marie Curie

The field of nuclear chemistry began when Marie Curie (1867-1934) and her husband, Pierre Curie (1859-1906), discovered radioactivity. In 1898, Marie Curie, a Polish-born chemist, coined the word "radioactivity" to describe peculiar behavior of elements she and her husband had discovered. They shared a Nobel Prize in 1903 for their discovery of radioactivity. Marie Curie was awarded a second Nobel in 1911 for her discovery of the elements radium and polonium.

Marie Curie began her career as a scientist at the University of Sorbonne in Paris. There, she was the first woman to graduate with a degree in physics (1893). Later in 1894, she received a degree in mathematics. For her work on radioactivity, she was the first woman to receive a Nobel Prize and the first person to receive two Nobel prizes. She was also the first woman professor at the University of Sorbonne. During World War I, she used her knowledge of radioactivity and her passion for applying this technology to medicine to organize mobile X-ray machines that could go from hospital to hospital. She championed radiation therapy as a treatment for cancer.

Rosalyn Sussman Yalow



Rosalyn Sussman was born in New York City in 1921. Rosalyn studied physics and chemistry in college, and then went on to the University of Illinois, where she earned her doctorate in nuclear physics. There she met and married Aaron Yalow.

In 1950, Rosalyn Yalow began researching medical uses of radioactive substances at the VA Hospital in the Bronx. She and her research partner, Solomon Berson, developed radioimmunoassay, or RIA. RIA is a technique that uses radioactive isotopes to measure tiny concentrations of biological substances and certain drugs in blood and other body fluids.

One early application of RIA was in diabetes research, which was especially significant to Yalow because her husband was diabetic. RIA's current uses include screening donated blood, determining effective doses of medicines, testing hormone levels in the blood, and treating certain children with growth hormones.

Yalow was awarded the Nobel Prize in Physiology or Medicine in 1977. She was the second woman to win in that category.

22.2 Carbon Reactions

What would the world be like without the sun? The world relies on the sun's energy more than you may realize. In fact, 99 percent of our energy needs are met by the sun. We get the rest of our energy namely by using fossil fuels—which were derived from the sun's energy millions of years ago. In this section you will learn about carbon reactions, such as the combustion of fossil fuels. Your body also happens to use a combustion reaction to get energy from the food you eat. By the end of the section, you will better understand the role of carbon reactions in food production, air pollution, and global warming.

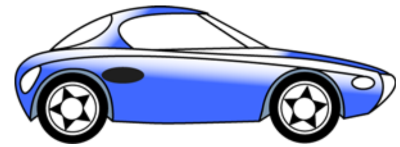
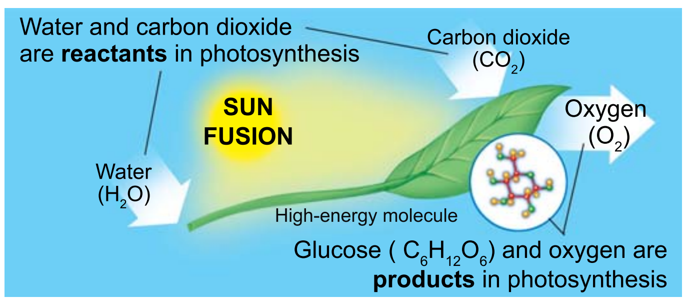


Figure 22.7: *Whether you walk or ride in a car, you are using carbon reactions to travel from place to place.*

Photosynthesis

Plants convert the sun's energy into products we use

Recall that the sun produces its energy from a nuclear reaction called fusion. Inside the sun, hydrogen atoms "fuse" to produce helium and a lot of energy. The fusion reactions in the sun produce enough energy to illuminate and warm our planet Earth. This energy reaches the planet as visible and ultraviolet light, and infrared radiation (heat). It is easy to take all this energy for granted because is it free and clean. Most importantly, plants, using the process of photosynthesis, can Use energy from the sun to convert carbon dioxide and water into glucose, a type of sugar. Glucose in turn, is converted into more complex molecules that are used by animals—including humans. Fruits, vegetables, cotton, and wood are just some of the many plant products you may use of during a single day.



Photosynthesis

Photosynthesis is a process that is performed by plants, fresh water algae, saltwater algae, and some bacteria. In this process, special pigments absorb energy from the sun. This energy is used to convert water and carbon dioxide (CO_2) to glucose ($C_6H_{12}O_6$) and oxygen (O_2). Photosynthetic organisms (those that perform photosynthesis) produce glucose for their own energy and structural needs. Humans then use what plants produce for food, building materials, writing materials, clothing, and even medicines.

Carbon reactions and fossil fuels

Cars burn fossil fuels for energy

The sun helps make Earth very livable. More and more, however, we are requiring additional energy in the form of fossil fuels. The world's reliance on fossil fuels has increased steadily since the beginning of the Industrial Revolution in the mid-eighteenth century. Today, we use fossil fuels (like natural gas, kerosene, and coal) for home heating, for the production of electricity, and to run our machines. The machine we depend on most—the automobile—allows us to ride instead of walk to the places we want to go. A car converts the energy stored in fossil fuel (gasoline) into motion through a common chemical reaction called *combustion*.

Use of fossil fuels affects the environment

Unfortunately, our dependence on fossil fuels comes at a cost. When you put gasoline into a car, you are providing one of the reactants for a combustion reaction. Gasoline and oxygen react to produce carbon dioxide and water. Because combustion occurs in the engine at a high temperature and pressure, other products are produced as well. Because we can't see some of these products, it is easy to forget they are there.

Earth's atmosphere is a mixture of gases. The composition of the air is 78 percent nitrogen gas (N_2), 21 percent oxygen (O_2), 0.037 percent carbon dioxide (CO_2), 1 percent argon (an unreactive gas), traces of other gases, and some water vapor.

The atmosphere is mostly nitrogen gas

Nitrogen gas (N_2) is particularly abundant in the atmosphere because it isn't very reactive. However, nitrogen is essential for making molecules called proteins. Plants called legumes (like beans and peas) incorporate airborne nitrogen into protein for their own use. Other plants obtain nitrogen from fertilized soil. Your body obtains nitrogen for making proteins when you eat foods (vegetables and meat) that are high in protein.

O_2 comes from photosynthesis

Unlike nitrogen, oxygen (O_2) is a reactive, flammable gas. The great abundance of nitrogen (N_2) in the atmosphere effectively dilutes the O_2 so that things don't burn out of control every time a fire is started! Living plants and organisms are responsible for keeping enough oxygen in the atmosphere.

Carbon dioxide

Natural sources release about 150 billion tons of carbon dioxide each year. Much of this carbon dioxide is absorbed by natural processes, such as photosynthesis. By burning fossil fuels and clearing land for development, we put a strain on Earth's ability to manage CO_2 levels. For example, the amount of CO_2 in the atmosphere has increased by 30 percent since the beginning of the Industrial Revolution. Additionally, the average surface temperature of the planet has increased 0.6 to 1.2°F since the mid-1800s. These increases are not huge, but they are enough to have warmed the north pole and caused the sea level to rise 4 to 10 inches.

Global warming

Too much CO_2 in the atmosphere causes global warming

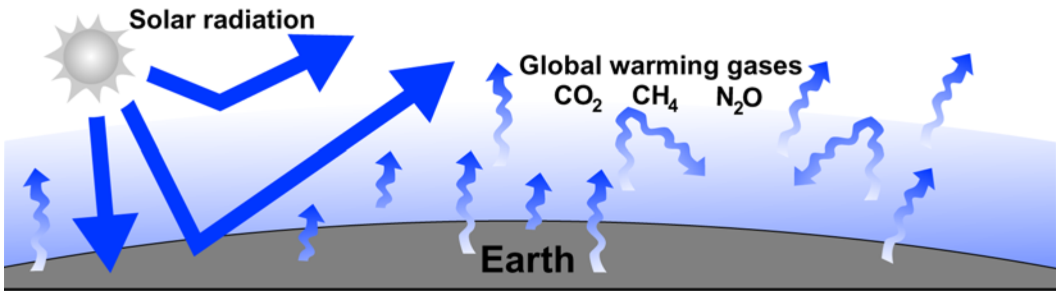
Compared to N_2 and O_2, there is very little carbon dioxide (CO_2) in the atmosphere. This may be surprising to you because you may have heard that increases in CO_2 in the atmosphere cause global warming. The amount of CO_2 that we have in our atmosphere is just enough to trap heat from the sun to make Earth warm and comfortable. The planet would be too warm with more CO_2 and too cold with less CO_2. When we use fossil fuels, we add more CO_2 to the atmosphere. The phrase **global warming** refers to our ability to increase the temperature of the planet's climate by increasing the amount of CO_2 in our atmosphere. In the United States, each person contributes about 6.6 tons of CO_2 every year! The world produces about 7 billion tons per year.

Car emissions are pollutants

The amount of CO_2 produced by a single car is less than that produced by a large factory or power plant. However, many of us use cars every day and carbon dioxide emissions add up. The word **emissions** refers to the airborne gases and particles that come out of the car's tailpipe when it runs. The combined CO_2 emissions and other pollution from cars on a day-to-day basis have caused many of our large cities to be noticeably hazy and smoggy.

Auto emissions	harm
carbon dioxide	major contributor to global warming
carbon monoxide	deadly gas
nitrous oxides	contribute to acid rain
ozone	irritation to eyes and lungs
hydro-carbons	cancer causing

Figure 22.8: *Ways in which automobile emissions affect air quality.*



Global warming

Some of the solar radiation that reaches Earth is absorbed by its surface, and some is reflected and exits the atmosphere. However, heat that builds up within the Earth's atmospheres is trapped by global warming gases. The main global warming gases are carbon dioxide (CO_2), methane, (CH_4), and nitrous oxide (N_2O). You will learn more about global warming in chapter 26.

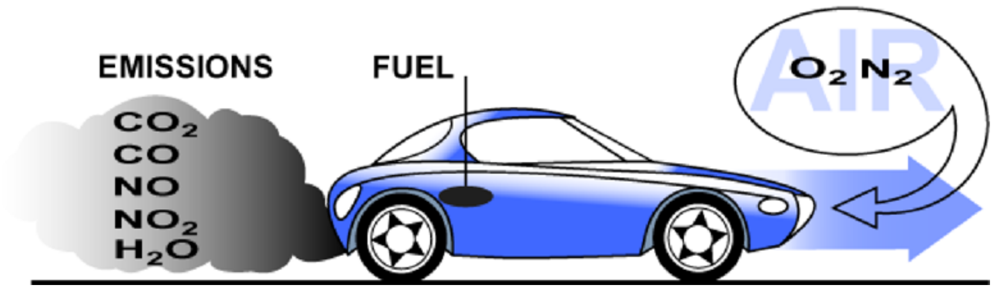
The combustion reaction in cars

Incomplete combustion means more air pollution

Fuel is a mixture of molecules called hydrocarbons. As the name suggests, these molecules only contain hydrogen and carbon. The energy of these valuable molecules is stored in the carbon-carbon and carbon-hydrogen bonds. Hydrocarbons become pollutants when they are incompletely burned during combustion or when they evaporate during refueling or from the engine while it cools. Hydrocarbons can react with nitrogen oxides and sunlight to make ozone. Both ozone and hydrocarbons are toxic pollutants.

The problems with nitrogen oxides

During combustion of fuel in a car, the high temperature and high pressure in the engine causes nitrogen in the air (which is typically unreactive) to convert to nitrogen oxides. Nitrogen oxides are reactants in the formation of ozone, a irritant to eyes and lungs. Nitrogen oxides also mix with water in the atmosphere, forming nitric acid, a component of acid rain.



Carbon monoxide is a toxic gas

Complete combustion reactions produce only carbon dioxide. Incomplete combustion reactions also produce carbon monoxide (CO). This small molecule "looks" like oxygen to your body so your body uses CO instead of oxygen. For this reason, high concentrations of CO can be deadly. Lower concentrations found in areas with heavy traffic can be harmful to people with heart or lung disease.

The catalytic converter

The catalytic converter, introduced in the 1970s, reduces hydrocarbon and carbon monoxide emissions by converting these molecules to carbon dioxide and water. Improvements to the catalytic converter over the years have greatly reduced these emissions.

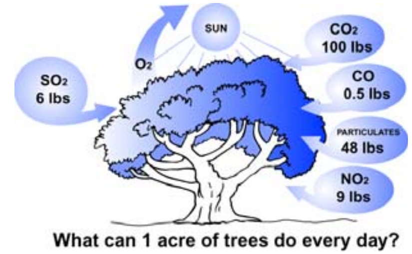


Figure 22.9: *Trees help consume carbon dioxide and other pollutants.*

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Reducing CO_2

One acre of trees provides oxygen for about 20 people each day. This same acre can absorb emissions, including CO_2 (see Figure 22.10).

Questions to discuss with your friends:

- Trees greatly benefit our air quality, but can they solve global warming?
- Why might trees not be a good enough solution to global warming?
- What can you do to reduce how much CO_2 you produce?

Chapter 22 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. alpha particle	a. A word to describe isotopes that undergo fission
2. radioactive	b. The part of an atom that contains protons and neutrons
3. beta particle	c. Two neutrons and two protons released from the nucleus of an atom
4. radioactive decay	d. An electron that splits off of a neutron and is released from the nucleus of an atom
5. fission	e. A nuclear reaction that involves the splitting of a heavy nucleus into a lighter nucleus
	f. Radioactive isotopes experience this when they undergo fission

Set Two

1. fusion	a. This type of nuclear reaction occurs in the sun
2. gamma rays	b. The average time for half the amount of a radioactive element to decay
3. half-life	c. An atom that is distinguished by the number of neutrons in its nucleus
4. isotope	d. A form of electromagnetic radiation released during radioactive decay
5. nuclear reaction	e. The mixing of baking soda and vinegar causes this kind of reaction
	f. Fission and fusion are examples of this kind of reaction

Concept review

1. In your own words, describe the difference between fusion and fission. Why do elements undergo fusion or fission spontaneously?
2. In a short paragraph, contrast nuclear reactions with chemical reactions.
3. Write the isotope notation for hydrogen-3, hydrogen-2 and hydrogen-1. List the number of neutrons, protons and electrons in each of these isotopes.
4. What are the differences between alpha decay and beta decay? Draw a labeled diagram showing each of these particles.
5. Explain how photosynthesis and respiration are related to carbon reactions. Write out these reactions in your response.
6. Describe the chemical composition of the Earth's atmosphere.
7. Explain why our use of cars can be cited as one cause of global warming.
8. List 10 products that you use or consume that are made from plants.

Problems

1. At the beginning of the student reading you were asked, "Which atoms could you combine to make gold?" Use a periodic table with the mass numbers of stable isotopes to write out a fusion reaction and fission reaction for gold. Use the isotope notation for referring to each isotope in the reaction (i.e., the notion for hydrogen-2 would be ${}^{2}_{1}H$). Additionally, if your reactions involve alpha or beta decay, or the gain or loss of a neutron, be sure to indicate these aspects in your written reaction.
   a. Fusion:
   b. Fission:

2. An isotope decreased to one-fourth its original amount in 18 months. What is the half-life of this radioactive isotope?

3. The decay series for uranium-238 and plutonium-240 are listed below. Above each arrow, write "a" for alpha decay or "b" for beta decay to indicate which type of decay took place at each step.

   a. ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa \rightarrow {}^{234}_{92}U \rightarrow {}^{230}_{90}Th \rightarrow$

   ${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn \rightarrow {}^{218}_{84}Po \rightarrow {}^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi \rightarrow$

   ${}^{214}_{84}Po \rightarrow {}^{210}_{82}Pb \rightarrow {}^{210}_{83}Bi \rightarrow {}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb$

   b. ${}^{240}_{94}Pu \rightarrow {}^{240}_{95}Am \rightarrow {}^{236}_{93}Np \rightarrow {}^{232}_{91}Pa \rightarrow {}^{232}_{92}U \rightarrow$

   ${}^{228}_{90}Bi \rightarrow {}^{224}_{88}Ra \rightarrow {}^{224}_{89}Ac \rightarrow {}^{220}_{87}Fr \rightarrow {}^{216}_{85}At \rightarrow$

   ${}^{212}_{83}Bi \rightarrow {}^{212}_{84}Po \rightarrow {}^{208}_{82}Pb \rightarrow {}^{208}_{83}Bi$

4. All plants use the process of photosynthesis. However, this process wasn't always understood. In one classic experiment, a small plant and its soil were weighed. The plant was given only water for a solid year. At the end of the year, the plant weighed much more than it did at the first of the year. The soil weighed the same amount. Where did the extra weight of the plant come from?

5. Could you get rich making gold from fission and fusion reactions? Why or why not?

6. Due to radioactive decay, a sample of an isotope decreased to one-half its original amount in 6 days. What is the half-life of this radioactive isotope?

7. Answer the following:
   a. Cesium-137 is used to investigate soil erosion. This radioactive isotope naturally undergoes beta decay to become a different element. How many neutrons and protons will the different element have? What is this element?
   b. The half-life of cesium-137 is 30 years. Make a graph that shows the radioactive decay of cesium-137 over a period of 300 years. Place time on the x-axis of the graph, and amount of cesium-137 on the y-axis. The starting amount of cesium-137 is 100 atoms. Be sure to title the graph and label the axes.

Applying your knowledge

1. Mining for gold is an active industry. In order for mining companies to grow as businesses, they need to discover new sites that are rich in gold or other valuable minerals and element. Research in your library or on the Internet to find out about mining for gold. What do experts say about how much gold remains to be discovered?

2. Organize a debate in your class on the topic of nuclear energy and technology. What are the pros of using nuclear energy and technology? What are the cons? Prior to the debate, assign teams to the pro and con side and figure out with the class how the debate will be scored.

3. What is the difference between strong nuclear force and gravity? Are there other forces in the universe besides strong nuclear force and gravity? If so, what are these forces and how are they different from gravity and strong nuclear force?

4. The Earth's atmosphere differs from the atmospheres of Mars and Venus. Find out the chemical composition of the atmospheres on these planets. Explain why Earth's atmosphere is suitable for life, but the atmospheres of Mars and Venus are not.

5. Read a recent article about global warming. Write a short summary about the article and a brief paragraph explaining your opinions about the article and global warming.

6. Make a brochure that describes the causes of, the consequences of, and the solutions to global warming. Include the economic impact of global warming in your brochure. Do careful research in your library and on the Internet to make this brochure. Include quotations from individuals who are experts on this subject. Experts might be individuals who study global warming at a local college or university. Add your own color graphics to your brochure.

7. The Clean Air Act is an important piece of environmental law. The act was passed in 1970 and then amended in 1990. The purpose of this act is to reduce the number of airborne pollutants in our atmosphere. Most of these pollutants are end-products of chemical reactions that result from industrial processes and our use of gasoline-powered cars.

   Identify three chemical reactions that are used in industry that result in airborne pollutants. Find out how the Clean Air Act has regulated the industries that produce these pollutants

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   Obeying the Clean Air Act means that a polluting company, consumers (you), and/or tax-payers have to pay for fixing the causes of the pollutants. This could mean cleaning facilities or changing to newer, non-polluting technologies.

   List five things companies could do to reduce pollution. These costs are usually passed on to consumers through higher prices.

   List five additional problems caused by airborne pollutants that society must pay for. Is the cost of each problem paid by taxes or by the individuals affected by the pollution?