What does the word "chemical" mean to you? Does it make you think of strange, bubbling concoctions in test tubes, mixed by a scientist in a white lab coat? You might have heard or read about a "hazardous chemical spill", or you might have experimented with chemicals in a science lab. Would it surprise you to know that YOU are a mixture of chemicals? So is a block of wood or a glass of orange juice. In fact, the word chemical is used to describe any substance that is composed of atoms bonded together. Water (H₂O) is a chemical. Sodium chloride (NaCl) is a chemical. Your body contains thousands of different chemicals. Not all chemicals are hazardous to your health! Many chemicals are necessary for growth and survival.

All of the millions upon millions of different chemicals are made of only 92 elements combined in different ways. Just as you can spell thousands of words with the same 26 letters, you can make all the variety of chemicals from 92 elements.

By rearranging atoms you can turn wood into ashes or iron and air into rust. By rearranging particles inside the atom, you can even turn lead into gold!

Key Questions

- How can you predict how certain atoms will combine to form compounds?
- Why do nuclear reactions involve HUGE amounts of energy?
- Are all forms of radiation dangerous?
11.1 Chemical Bonds

Most matter is in the form of compounds. You learned in the last unit that water (H₂O) is a compound made of hydrogen and oxygen atoms. If a substance is made of a pure element, chances are it will eventually combine with other elements to make a compound. For example, an iron nail combines with oxygen in water or air to make a compound called iron oxide, better known as rust. Why do atoms tend to combine with other atoms?

What are chemical bonds?

Electrons form chemical bonds

When atoms combine, they form chemical bonds. A chemical bond forms when atoms transfer or share electrons. Two atoms that are sharing one or more electrons are chemically bonded and move together. In a water molecule, each hydrogen atom shares its single electron with the oxygen atom at the center. Almost all the elements form chemical bonds easily. This is why most of the matter you experience is in the form of compounds.

A chemical bond forms when atoms transfer or share electrons.

Chemical bonds determine chemical properties

The chemical properties of a substance come from how it forms chemical bonds with other substances. For example, the nonstick coating on cooking pans is “non-stick” because it does not form chemical bonds with substances in food. The active ingredient in aspirin works because it bonds with chemicals in the body called prostaglandins and prevents them from creating swelling that causes pain.

The properties of a materials depend much more on the molecule than on the elements the molecule is made of. Aspirin is made from carbon, hydrogen, and oxygen. By themselves, these elements do not have the property of reducing pain. Other molecules formed from the same elements have different properties than aspirin. For example, polyethylene plastic wrap and sugar are also made from carbon, oxygen, and hydrogen. The pain-relieving properties of aspirin come from the way the atoms bond together and the particular shape of the aspirin molecule (Figure 11.1).
Chemical bonds

Atoms form bonds to reach lower energy. Chemical bonds release energy when they form. 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. Energy is released when atoms form chemical bonds because chemically bonded atoms have lower energy than free atoms. Like a ball rolling downhill, atoms collect into molecules because the atoms have lower energy when they are together in molecules (Figure 11.2).

Valence electrons form chemical bonds. In Chapter 9 you learned that the outer electrons (valence electrons) in an atom form chemical bonds. For example, carbon has four valence electrons and can make up to four chemical bonds with other atoms. Oxygen needs 2 valence electrons and therefore can form bonds with up to two atoms.

Two types of chemical 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. In a covalent bond the electrons are shared between atoms.

Ionic bonds

An ion is an atom or molecule that has a net positive or negative electric charge. Atoms that either gain or lose an electron become ions. In an ionic bond, the atoms that give up electrons become positive. The atoms that take electrons become negative. The positive and negative ions are attracted to each other, making the ionic bond.

Alkali metals tend to form ionic bonds

The alkali metals with one valence electron have a tendency to give up one electron. The halogens with seven valence electrons have a tendency to take one electron (Figure 11.3). If you put an alkali metal (Na) with a halogen (Cl), you get an ionic bond because one atom has a strong tendency to lose an electron and the other has a strong tendency to gain one.

Multiple ionic bonds

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.
**Covalent bonds**

**How covalent bonds form**

In a covalent bond, valence electrons are *shared* between atoms, not transferred. The bonds between hydrogen and oxygen in a water molecule are an example of covalent bonds. The oxygen atom in the molecule needs two electrons to have eight valence electrons. Hydrogen atoms need only one electron to have two valence electrons, also a stable number. When a hydrogen atom bonds to an oxygen atom, the electrons act like ties between the two atoms (Figure 11.4).

**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 nearly evenly 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 11.5). The hardness of diamonds is due to the fact that four covalent bonds must be broken to move each carbon atom.

**How are covalent and ionic bonds different?**

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). Molecules joined by covalent bonds tend to be much harder to separate into their individual atoms. Ionic compounds do not exist as individual molecules, but as groups of oppositely charged ions. Many ionic compounds separate into individual ions when dissolved in water.

**11.1 Section Review**

1. Explain why a hydrogen atom is more likely to combine with other atoms than a helium atom.
2. Our atmosphere consists of 21 percent oxygen in the form of O₂ molecules. Is the chemical bond between two oxygen atoms ionic or covalent? Explain your answer.
3. Lithium atoms easily combine with fluorine atoms. Is this an ionic or covalent bond? Explain your answer.
11.2 Chemical Reactions

Chemical reactions rearrange atoms into different molecules by breaking and reforming chemical bonds. If you leave an iron nail out in the rain, the gray surface soon turns reddish-brown with rust. Rust forms through a chemical reaction between iron in the nail and oxygen. Chemical reactions are the process through which chemical changes happen, like iron turning to rust.

**Chemical changes rearrange chemical bonds**

Ice melting is an example of a physical change. During a physical change, a substance changes its form but remains the same substance. A chemical change turns one or more substances into a different substances that may have different properties. An example of chemical change is burning wood into carbon dioxide, water, and ashes.

Using chemical changes

We use chemical changes to create materials with properties that are useful. The rubber in car tires is an example of a material that has been modified by chemical changes. A chemical change called vulcanization inserts pairs of sulfur atoms into the long chain molecules of natural rubber. The sulfur ties adjacent molecules together like rungs on a ladder and makes vulcanized rubber much harder and more durable.

Recognizing chemical change

A chemical reaction is a system of chemical changes that involves the breaking and reforming of chemical bonds to create new substances. A chemical reaction occurs when you mix baking soda with vinegar. The mixture bubbles violently as carbon dioxide gas, a new substance, is formed. The temperature of the mixture also gets noticeably colder. Bubbling, new substances, and temperature change, are all evidence of chemical change (Figure 11.6).

**Vocabulary**

- chemical reaction, reactant, product, chemical equation, activation energy, exothermic, endothermic, photosynthesis, respiration

**Objectives**

- Recognize the signs of chemical change
- Explain how energy is used or released by chemical reactions
- Write an equation for a chemical reaction

**Evidence of chemical change**

- **Bubbling**: A new gas is forming?
- **Temperature change**: Chemical bonds are changing?
- **Color change**: A new substance is forming?
- **Turns cloudy**: A new solid is forming?

**Figure 11.6**: Four observations that are evidence of chemical change.
Chemical equations are recipes for chemical reactions

**What are chemical reactions?**

A chemical reaction rearranges atoms in one or more substances into one or more new substances. Hydrogen reacts with oxygen to produce water and energy. Because so much energy is produced, hydrogen is used as fuel for rockets and may eventually replace gasoline in automobiles.

**Products and reactants in chemistry**

How do we show the chemical reaction between hydrogen and oxygen to produce water and energy? In cooking you start with ingredients that are combined to make different foods. In chemical reactions you start with reactants that are combined to make products. The reactants and products may include atoms, molecules, and energy. When hydrogen is used for fuel, two hydrogen molecules combine with one oxygen molecule to make two water molecules. Hydrogen and oxygen are the reactants. Water and energy are the products.

**Writing chemical reactions**

A chemical equation is an abbreviated way to show the exact numbers of atoms and molecules in a chemical reaction. In the equation above, \( \text{H}_2 \) represents a hydrogen molecule, \( \text{O}_2 \) represents an oxygen molecule, and \( \text{H}_2\text{O} \) is a water molecule. The little numbers (subscripts) tell you how many atoms of each element there are in one molecule. For example, the subscript 2 in \( \text{H}_2\text{O} \) means there are two hydrogen atoms in a water molecule. The large number 2 in “\( 2\text{H}_2\text{O} \)” tells you there are two molecules of \( \text{H}_2\text{O} \) in the reaction. To keep the numbers straight remember that the little numbers (subscripts) tell you how many atoms are in one molecule. The larger numbers (called coefficients) tell you how many molecules are in the reaction. If a number is not written it is understood to be “1.”

**Balancing a chemical equation**

A balanced equation means that the same number of atoms of each element appear in the products and in the reactants.

**Step 1:** Make sure that you have the correct chemical formula for each molecule that appears as a reactant or product.

**Step 2:** Write down the equation for the reaction.

**Step 3:** Count the number of atoms of each element in the reactants. Also, count the number of atoms of each element in the products.

**Step 4:** Adjust the coefficient of each reactant or product until the total number of each type of atom is the same on both sides of the equation. This is done by trial and error.

**Important reminder**

You can never change subscripts in order to balance an equation. For example, calcium chloride has the chemical formula, \( \text{CaCl}_2 \). You cannot change the subscript on Cl from 2 to 3 and make \( \text{CaCl}_3 \) to get an extra chlorine atom. Changing subscripts creates a totally different molecule. You can only change coefficients to balance equations.
Conservation of mass and energy

Conservation of mass
Chemical reactions do not create new atoms; they rearrange existing atoms to make new substances. *This means that the mass of the reactants must be equal to the mass of the products.* That is why chemical equations must be balanced. A balanced chemical equation conserves mass because the same number of atoms of each element appear on both sides of the equation.

Energy involved in two ways
During a chemical reaction, the bonds in the reactants must be broken so that atoms are available to form new bonds. Energy is involved in chemical reactions in two ways: (1) energy is used to break the bonds in the reactants, and (2) energy is released when new bonds form.

Activation energy
The energy needed to break chemical bonds in the reactants is called the *activation energy* of the reaction. If you put pure hydrogen and oxygen together nothing happens until you make a spark (Figure 11.7). The spark supplies the activation energy to start the reaction.

Exothermic reactions
If forming new bonds releases *more* energy than it took to break the old bonds, the reaction is said to be *exothermic.* *Exothermic reactions release the excess energy.* Once started, exothermic reactions tend to keep going because each reaction releases enough activation energy to start the reaction in neighboring molecules. The reaction above is exothermic.

Endothermic reactions
If forming new bonds in the products releases *less* energy than it took to break the original bonds in the reactants, the reaction is *endothermic.* *Endothermic reactions absorb energy.* These reactions do not usually keep going unless energy is supplied. For example, if you make a spark in water, a few molecules might react but reactions do not occur in the rest of the water.

Figure 11.7: Energy from a spark breaks the initial bonds to start an exothermic reaction in which hydrogen molecules combine with oxygen molecules (burn) to become water.
The importance of photosynthesis

The energy that supports life on Earth starts with a reaction that takes energy from sunlight and stores it as chemical bonds in molecules of glucose. This reaction is called **photosynthesis** (Figure 11.8). Photosynthesis occurs mostly in plants and in some types of bacteria. Animals (including ourselves) also get energy from photosynthesis, because we eat plants or other animals that eat plants. Nearly all the energy in living things can be traced to this important reaction.

Photosynthesis releases oxygen

Photosynthesis also produces the oxygen in our atmosphere. Without plants, Earth’s atmosphere would have no oxygen, and could not support life. Although oxygen is a very common element, it is usually trapped by rocks and minerals in molecules like calcium carbonate (CaCO$_3$).

Photosynthesis removes CO$_2$

Photosynthesis removes carbon dioxide from the atmosphere. For every glucose molecule produced, six molecules of carbon dioxide are removed from the air, and six molecules of oxygen are produced. Carbon dioxide absorbs infrared radiation and therefore traps heat in the atmosphere. If too much carbon dioxide is present, the Earth cannot cool itself by radiating energy into space. Higher levels of carbon dioxide may be responsible for the warming of our planet by several degrees over the past 200 years. Can you think of ways to stabilize carbon dioxide levels?

Respiration

Animals who eat plants get energy by breaking up glucose molecules. This process is called **respiration**. The reactions of respiration proceed in many steps, but the end result is that glucose and oxygen are used up and carbon dioxide and water are produced. Respiration is almost the reverse of photosynthesis. It releases the energy that originally came from the sun.

11.2 Section Review

1. Give four observations that are evidence of chemical change.
2. Write a balanced chemical equation for burning hydrogen in oxygen to make water.
3. Explain why a balanced chemical equation conserves mass.
4. Explain how activation energy relates to the energy used or produced by a chemical reaction.
11.3 Nuclear Reactions

You would be very surprised if you saw a bus turn itself into two cars and a van! A radioactive atom does something almost as strange. If left alone, an atom of uranium eventually turns into an atom of lead! This radioactive decay is one example of a nuclear reaction. Nuclear reactions change the nucleus of an atom. Until just 100 years ago people looked for a way to turn lead into gold. With today’s understanding of nuclear reactions, it is now possible. However, we don’t do it very often because the process is much more expensive than the gold it produces!

Nuclear reactions are different than chemical reactions

Because they affect the nucleus itself, nuclear reactions can change one element into a different element. Nuclear reactions can also change an isotope into a different isotope of the same element. Remember, isotopes of the same element have the same number of protons but different numbers of neutrons in the nucleus. By comparison, chemical reactions do not change the types of atoms. Chemical reactions only rearrange atoms into different compounds.

Nuclear reactions involve much more energy than chemical reactions. The energy in a nuclear reaction is much greater because nuclear reactions involve the strong nuclear force, the strongest force in the universe. Chemical reactions involve electrical forces. The electrical force acting on an electron far from the nucleus is much smaller than the strong force acting on a proton or neutron inside the nucleus. The difference in strength between the forces involved is the reason nuclear reactions are so much more energetic than chemical reactions (Figure 11.9).

Mass and energy in nuclear reactions

Mass and energy are conserved together but not separately in nuclear reactions. This is because nuclear reactions can convert mass into energy. If you could take apart a nucleus and separate all of its protons and neutrons, the separated protons and neutrons would have more mass than the nucleus does all together. This bizarre fact is explained by Einstein’s formula \( E = mc^2 \), which tells us that mass \( m \) can be converted to energy \( E \), when multiplied by the speed of light \( c \) squared. The mass of a nucleus is reduced by the energy that is released when the nucleus comes together. You’ll learn more about this important relationship in Chapter 12.
Nuclear reactions and energy

Energy of the nucleus

When separate protons and neutrons come together in a nucleus, energy is released. Think about many balls rolling downhill (Figure 11.10). The balls roll down under the force of gravity and potential energy is released. Protons and neutrons are attracted by the strong nuclear force and also release energy as they come together. The more energy that is released, the lower the energy of the final nucleus. The energy of the nucleus depends on the mass and atomic number. The nucleus with the lowest energy is iron-56 with 26 protons and 30 neutrons (the low point on the graph below). Protons and neutrons assembled into nuclei of carbon or uranium have higher energy so appear higher on the graph.

Nuclear energies are very large

The graph compares the energy of the nucleus in one kilogram of matter for elements 2 (helium) through 92 (uranium). The units of energy are hundreds of trillions \((10^{12})\) of joules per kilogram of material! Nuclear reactions often involve huge amounts of energy as protons and neutrons are rearranged to form different nuclei. A nuclear reaction releases energy when it rearranges protons and neutrons to make a new nucleus that is lower in energy on the graph (Figure 11.11). A nuclear reaction uses energy when the protons and neutrons form a nucleus that is higher in energy on the graph.

Figure 11.10: Energy is released when balls roll downhill, to a lower energy level.

Figure 11.11: A nuclear reaction that changed 1 kilogram of uranium into 1 kg of iron would release 130 trillion joules of energy.
**Fusion reactions**

**Writing nuclear reactions**
Nuclear reactions are written using symbols for the elements, like chemical reactions. The difference is that the mass number is important in nuclear reactions. Remember from Chapter 9, the mass number is the total number of protons plus neutrons in the nucleus. In a nuclear reaction each atom is written with a superscript to indicate the mass number. In an equation for a nuclear reaction, the isotope carbon-12 is written $\text{C}^{12}$.

**Fusion reactions**
Fusion reactions release energy if the final nucleus has lower energy than the initial nuclei (Figure 11.12). A kilogram of $\text{C}^{12}$ contains 104 trillion joules (TJ) of nuclear energy according to the graph. A kilogram of $\text{Mg}^{24}$ has 48 TJ of nuclear energy. An astounding 56 trillion joules are released if the protons and neutrons in one kilogram of $\text{C}^{12}$ are rearranged to make one kilogram of $\text{Mg}^{24}$ nucleus. The fusion reaction to make magnesium from carbon would actually go through a series of steps, but the end result would be the same release of energy.

**Fusion reactions need very high temperatures**
Positively charged nuclei repel each other. Two nuclei must get very close for the attractive strong nuclear force to overcome the repulsive electric force. One way to make two nuclei get close is to make the temperature very high. At very high temperatures kinetic energy slams two nuclei together with enough force to almost touch, allowing the strong force to take over and initiate a fusion reaction. The hydrogen fusion reactions in the core of the sun occur at a temperature of about 15 million degrees Celsius.

**Density and fusion power**
A single fusion reaction makes a lot of energy for a single atom. But a single atom is tiny. To produce enough power to light a single 100-watt bulb requires $10^{14}$ fusion reactions per second. The density of atoms must be large enough to get a high rate of fusion reactions.

**Fusion in the sun**
Stars like the sun make energy from fusion reactions because the core of a star is both hot and very dense. The density at the core of the sun is so high that a tablespoon of material weighs more than a ton. The primary fusion reaction that happens in the sun combines hydrogen nuclei to make helium, converting two protons and two electrons into two neutrons along the way. All of the energy reaching Earth from the sun comes ultimately from these fusion reactions in the sun’s core.
Fission reactions

Fission reactions

For elements heavier than iron, breaking the nucleus up into smaller pieces (fission) releases nuclear energy (Figure 11.13). For example, a kilogram of uranium-235 (atomic number 92) has about 123 trillion joules (TJ) of nuclear energy. A fission reaction splits the uranium nucleus into two pieces. Both pieces have a lower atomic number, and are lower on the energy of the nucleus graph. The fission of a kilogram of uranium into the isotopes molybdenum-99 and tin-135 releases 98 trillion joules. This amount of energy from a golf-ball-sized piece of uranium is enough to drive an average car 19 million miles!

Fission is triggered by neutrons

A fission reaction typically starts when a neutron hits a nucleus with enough energy to make the nucleus unstable. Fission breaks the nucleus into two smaller pieces and often releases one or more extra neutrons. Some of the energy released by the reaction appears as gamma rays and some as kinetic energy of the smaller nuclei and the extra neutrons.

Chain reactions

A chain reaction occurs when the fission of one nucleus triggers fission of many other nuclei. In a chain reaction, the first fission reaction releases two (or more) neutrons. The two neutrons hit two other nuclei and cause fission reactions that release four neutrons. The four neutrons hit four new nuclei and cause fission reactions that release eight neutrons. The number of neutrons increases rapidly. The increasing number of neutrons causes more nuclei to have fission reactions and enormous energy is released. The fission chain reaction of uranium is how nuclear power plants release nuclear energy.

Radioactive materials

The products of fission usually have too many neutrons to be stable and are radioactive. Radioactive means the nucleus continues to change by ejecting protons, neutrons, or other particles. A radioactive nucleus may also change a neutron into a proton and an electron, or vice-versa. Both Mo\(^{99}\) and Sn\(^{135}\) are radioactive. Radioactive atoms may be dangerous because they continue to give off energy, some for a long time. The term nuclear waste includes used fuel from nuclear reactors that contains radioactive isotopes such as molybdenum-99 and tin-135.

Figure 11.13: Fission releases energy because the uranium nucleus is higher in energy than tin (Sn) or molybdenum (Mo).
Radioactivity and radiation

**Radioactive decay**
If an atomic nucleus is unstable for any reason, the atom undergoes a type of nuclear reaction called **radioactive decay**. The word *decay* means to *break down*. In radioactive decay, the nucleus of an atom spontaneously breaks down and emits subatomic particles and radiation. The three most common types of radioactive decay are: alpha decay, beta decay, and gamma decay.

**Alpha decay**
In **alpha decay**, the nucleus ejects two protons and two neutrons. Check the periodic table and you can quickly show that two protons and two neutrons are the nucleus of a helium-4 (He\(^4\)) atom. Alpha radiation is actually fast-moving He\(^4\) nuclei. When alpha decay occurs, the atomic number is reduced by two because two protons are removed. The atomic mass is reduced by four because two neutrons go along with the two protons. For example, uranium-238 undergoes alpha decay to become thorium-234.

**Beta decay**
**Beta decay** occurs when a neutron in the nucleus splits into a proton and an electron. The proton stays in the nucleus, but the high energy electron is ejected and is called beta radiation. During beta decay the atomic number increases by one because one new proton is created. The mass number stays the same because neutrons and protons both have a mass number of 1.

**Gamma decay**
**Gamma decay** is how the nucleus gets rid of excess energy. In gamma decay the nucleus emits a high-energy photon (electromagnetic radiation), but the number of protons and neutrons stays the same. The nucleus decays from a state of high energy to a state of lower energy. Gamma ray photons are energetic enough to break apart other atoms, making them dangerous to living things. Gamma rays require heavy shielding to stop. Alpha and beta decay are often accompanied by gamma radiation from the same nucleus.

**Radiation**
The word radiation means the flow of energy through space. There are many forms of radiation. Light, radio waves, microwaves, and x-rays are forms of electromagnetic radiation. The energy in alpha and beta radiation comes from moving particles. Radiation is dangerous when it has enough energy to break chemical bonds in molecules. Ultraviolet light, gamma rays and x-rays are some forms of radiation that can be harmful to living things in large quantities.

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**Figure 11.14:** The three most common radioactive decay reactions.
11.3 NUCLEAR REACTIONS

Half-life

Chance and radioactivity

Americium-241 is a radioactive isotope used in household smoke detectors. If you were looking at an individual americium-241 atom, it would be impossible to predict when it would decay. However, if you have a large collection of americium atoms, then the rate of decay becomes predictable. For americium-241, it is known that half of the atoms decay in 458 years. Therefore, 458 years is the half-life of americium-241. The half-life is the time it takes for one half of the atoms in any sample to decay.

The half-life of carbon-14

Every radioactive element has a different half-life, ranging from fractions of a second to millions of years, depending on the specific isotope. For example, the half-life of carbon-14 is about 5,700 years. If you start out with 200 grams of C\textsuperscript{14}, 5,700 years later only 100 grams will still be carbon-14. The rest will have decayed to nitrogen-14 (Figure 11.15). If you wait another 5,700 years, half of your 100 remaining grams of carbon-14 will decay, leaving 50 grams of carbon-14 and 150 grams of nitrogen-14. Wait a third interval of 5,700 years, and you will be down to 25 grams of carbon-14. One half of the atoms decay during every time interval of one half-life.

The half-life of different isotopes varies greatly

Uranium-238 has a half-life of 4.5 billion years. It was created in the nuclear reactions of exploding stars, the remains of which condensed to form the solar system. We can still find uranium-238 on Earth because the half-life is so long. The isotope fluorine-18 has a half-life of 1 hour, 50 minutes. This isotope is used in medicine. Hospitals have to make it when they need it because it decays so quickly. Any natural fluorine-18 decayed billions of years ago. Carbon-15 has a half-life of 2.3 seconds. Scientists who make carbon-15 in a laboratory have to use it immediately.

Radioactive decay series

Most radioactive materials decay in a series of reactions. For example, radon gas comes from the decay of naturally occurring uranium in the soil (Figure 11.16). Radon itself decays into lead in a chain of three alpha decays and two beta decays. Radon is a source of indoor air pollution in some houses that do not have adequate ventilation. Many people test for radon before buying a house.

Figure 11.15: Half the carbon-14 turns into nitrogen-14 every half-life. The half-life of C\textsuperscript{14} is 5,700 years.

Figure 11.16: Radon gas (Rn\textsuperscript{222}) is created by a chain of radioactive decay reactions starting with uranium.
Carbon dating

Living things contain a large amount of carbon. The isotope carbon-14 is used by archeologists to determine age. We find this isotope in the environment because it is constantly being produced in the upper atmosphere by cosmic rays—high energy particles from the sun and elsewhere in the universe. The ratio of carbon-14 to carbon-12 in the environment is a constant, determined by the balance between production and decay of carbon-14. As long as an organism is alive, it constantly exchanges carbon with the environment. Therefore, the ratio of carbon-14 to carbon-12 in the organism stays the same as in the environment.

When a living organism dies it stops exchanging carbon with the environment. All the carbon-12 in the organism remains because it is a stable isotope. Almost no new carbon-14 is created because most cosmic rays do not reach the ground. As the carbon-14 decays, the ratio of carbon-14 to carbon-12 slowly gets smaller with age. By measuring this ratio, an archeologist can tell how long it has been since the material was alive. Carbon dating works reliably up to about 10 times the half-life, or 57,000 years. After 10 half-lives there is not enough carbon-14 left to measure accurately. Carbon dating only works on material that has once been living, such as bone or wood.

How a smoke detector works

Smoke detectors contain a tiny amount of americium-241, a radioactive isotope that emits alpha radiation. When an alpha particle hits a molecule of air, it knocks off an electron, making the air ionized. The positive ion and negative electron are collected by positive- and negative-charged metal plates attached to the battery in the smoke detector. The flow of ions and electrons creates a tiny electric current that is measured by the electronics of the smoke detector. When smoke is in the air, particles of smoke interrupt the flow of ions and electrons. The electric current collected by the metal plates drops. The circuit in the smoke detector senses the drop in current and sounds the alarm.

11.3 Section Review

1. Sketch a graph showing the energy of the nucleus versus the atomic number and use the graph to explain what kinds of nuclear reactions release energy.
2. Write the nuclear reaction that represents the alpha decay of uranium-238.
3. If Americium-241 has a half life of 458 years, how long do you need to wait until only 1/4 of a sample if Am^{241} is left?
Cook or Chemist?

Measure accurately, stir, heat, carefully judge for reaction completion, and don't stick your finger in anything. If you're thinking about a scientist in the lab, well, that's one possibility. This also accurately describes the action of a chef in the kitchen. A chef is very much like a scientist. Precise mixing and temperature control lead to accurate, reproducible results in both situations. New ideas based on sound principles and trial-and-error produce new products for both the chemist and the chef.

What's food made of?

Look at the label of any packaged food in a supermarket and you'll find a table giving the Nutritional Facts for it. Along with a few other items, all such tables give the total amounts of fat, carbohydrates, and protein that the item contains. In fact, with few exceptions (vitamins and minerals being among them) all food is made of these three groups of molecules in varying proportions.

Cooking transforms food

What happens to food during cooking is due to changes in carbohydrate, fat, and protein molecules. Heat is thermal energy that manifests itself as the kinetic energy of molecules vibrating and moving. Cooking transforms food by the transfer of thermal energy to the food molecules. The transferred energy is used to rearrange molecules, break existing bonds and form new ones. These changes in the microscopic structure result in both microscopic and macroscopic changes in food.

Have you ever tried to “uncook” an egg? It’s not just difficult, it's impossible. In fact, it's impossible to “uncook” just about everything. Cooking transforms food irreversibly. One of the interesting features of the molecules that make up food is how they are delicately balanced in higher energy states. Food molecules originate in plants that harness energy from the sun into high-energy molecules through a chemical reaction called photosynthesis.

Simple molecules link together through other reactions inside plants to form the molecules that make up foods. The energy supplied in cooking tips those molecules over the edge irreversibly to a lower energy state from which they never return.

Eggs - a mass of proteins

Eggs have three parts: the white (90% water, 10% protein), the yolk (50% water, 34% fats, 16% protein) and the shell (calcium carbonate). Cooking an egg transforms the proteins. Proteins are very large, very long chains of amino acids linked together. Amino acids are the building blocks of all proteins, including the ones that make up our bodies.
Hard-boiled eggs

The reshaping of proteins from their natural shape is called denaturing. An egg’s protein molecules in their natural, uncooked state are loosely coiled in individual “globbs” held together by weak bonds between different parts of the amino acid chain. Because the molecules are able to move around, the egg white and yolk remain liquid. Heat gives the proteins enough energy to break those bonds and each protein strand begins to straighten out. If enough heat is added, the ends of each protein molecule join together in bridge-like bonds. Other links form at points along the protein strands. The network of bonds prevents individual molecules from moving around and the egg becomes solid.

When sugars are cooked, a number of chemical reactions occur. As sugars cook, water is released and caramelization takes place. This gives us the characteristic aroma of cooking. Baking bread causes a browning reaction to take place causing carbohydrates to react with the amino acids of proteins. This reaction is responsible for the wonderful browning of bread and contributes to the aroma and flavor of roasted coffee beans and chocolate.

Fats: A stable ingredient

Fats are also made mostly of carbon and hydrogen atoms. The lower the ratio of hydrogen to carbon, the more “unsaturated” the fat. Aside from providing energy, fats help transport molecules in and out of cells and are an important part of many hormones. Fats are very stable to heat, making them useful in cooking. Cooking oils, butter and margarine are part of this group. Along with providing flavor, cooking with fats is fast. Cooking oils can be heated to over 200°C without boiling, while water boils at a temperature of 100°C.

Questions:
1. List some microscopic changes in foods that occur when they are cooked.
2. Why is cooking an irreversible process?
3. Describe what happens to egg protein when it is cooked.
4. Is a completely fat free diet healthy? Explain your answer.

Carbohydrates: The sweet life

Carbohydrates, made mostly of carbon and hydrogen atoms, are much simpler than proteins. Small carbohydrate molecules are called sugars, because they are generally sweet. Sugars are “simple carbohydrates.” Sucrose (table sugar) and glucose are examples of simple carbohydrates. When simple sugars are linked together in long chains, “complex carbohydrates” are formed.
Understanding Vocabulary

Select the correct term to complete the sentences.

<table>
<thead>
<tr>
<th>ion</th>
<th>chemical reaction</th>
<th>chain reaction</th>
<th>activation energy</th>
<th>exothermic</th>
<th>reactant</th>
</tr>
</thead>
<tbody>
<tr>
<td>ionic</td>
<td>reactant</td>
<td>half-life</td>
<td>beta decay</td>
<td>endothermic</td>
<td>product</td>
</tr>
</tbody>
</table>

Section 11.1
1. Electrons in a(n) ____ bond are transferred from one atom to another.
2. Electrons in a(n) ____ bond are shared between atoms.
3. An atom that loses or gains an electron is called a(n) ____.

Section 11.2
4. Mixing baking soda and vinegar is an example of a(n) ____.
5. A chemical reaction that gets hot is ____.
6. In a chemical reaction, you start with ____ that are combined to make ____.
7. A chemical reaction that gets colder is ____.
8. To make water from hydrogen and oxygen, a spark provides the ____ needed to make the reaction happen.

Section 11.3
9. ____ can change one element into another element.
10. A(n) ____ occurs when the fission of one nucleus triggers the fission of many other nuclei.
11. In ____ an atomic nucleus ejects two protons and two neutrons.
12. In ____ a neutron in a nucleus splits into a proton and an electron.
13. In ____ the nucleus of an atom emits a high-energy photon but the number of protons and neutrons stays the same.

Reviewing Concepts

Section 11.1
1. Aspirin and plastic wrap are both made from carbon hydrogen and oxygen. Why are their properties so different?
2. Explain how energy is involved in the formation and breaking of chemical bonds.
3. What are the major difference between ionic and covalent bonds?
4. What makes a diamond one of the hardest materials on Earth?
5. Are the bonds in a water molecule covalent or ionic? Explain.

Section 11.2
6. Explain how a physical change is different from a chemical change and give one example of each.
7. How can you tell when a chemical change has occurred?
8. What happens to chemical bonds during a chemical reaction?
9. Explain how mass is conserved in a chemical reaction.
10. What is the activation energy of a chemical reaction?
11. In terms of energy and chemical bonds, how are exothermic and endothermic reactions different?
12. How does photosynthesis harness energy from the sun for animals to use?

Section 11.3
13. In what ways are chemical reactions similar to nuclear reactions? In what ways are they different?
14. How is a fusion reaction different from a fission reaction? Which reaction is responsible for all of the energy reaching Earth from the sun?
15. In a chemical reaction, balanced equations are written using the law of conservation of mass. Can this same law be applied to nuclear reactions? Explain your answer.
16. Why is the energy released from a nuclear reaction so much greater than the energy from a chemical reaction?
17. Summarize the three kinds of radioactive decay in the chart below.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Proton #change</th>
<th>Neutron #change</th>
<th>Ejected particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Solving Problems

Section 11.1

1. For each of the following decide the type of change indicated and label the event as a physical (P) or chemical (C) change.
   a. Hot, molten lead for making black-powder shot hardens in the mold.
   b. Steam rises from a cup of hot water.
   c. Lead nitrate solution added to sodium iodide solution produces a yellow solid.
   d. A “cold pack” used to treat injuries uses ammonium nitrate mixed with water. When activated, the pack gets very cold.
   e. When calcium carbonate is added to hydrochloric acid, bubbles of gas rise.
   f. Chewing food breaks it up into smaller pieces to prepare it for digestion.
   g. Pepsin, an enzyme in the stomach, breaks protein into smaller molecules.

2. With which elements would sodium most likely form a chemical bond? (Hint: more than one answer is possible)
   a. francium
   b. bromine
   c. hydrogen
   d. argon
   e. oxygen

3. Which elements would form a covalent bond?
   a. carbon and hydrogen
   b. sodium and fluorine

Section 11.2

4. Calcium carbonate antacids neutralize acids in your stomach. In the reaction, hydrochloric acid reacts with calcium carbonate to produce carbon dioxide and water. Use the balanced equation for the reaction to answer questions a through f.
   \[2\text{HCl} + \text{CaCO}_3 \rightarrow \text{CaCl}_2 + \text{CO}_2 + \text{H}_2\text{O}\]
   a. What are the reactants in the equation?
   b. What are the products in the equation?
   c. How many HCl molecules are used in the reaction?
   d. How many CO\(_2\) molecules are produced?
   e. How many atoms of oxygen are found in the reactants? How many are found in the products?
   f. How many hydrogen atoms are found in the reactants? How many hydrogen atoms are found in the products?

5. Use the chemical reaction below to answer questions a through d.

\[
\begin{align*}
\text{CH}_4 + 2\text{O}_2 & \rightarrow 2\text{H}_2\text{O} + \text{CO}_2 + \text{energy} \\
\text{methane} + \text{oxygen} & \rightarrow \text{water} + \text{carbon dioxide} + \text{energy}
\end{align*}
\]

   a. List the products and reactants in the equation.
   b. How many oxygen molecules react with methane to make the products?
   c. Suppose the amount of methane was doubled. How many oxygen molecules would be required? How many water molecules would be produced?
   d. Is the reaction above exothermic or endothermic?

6. Which of the following chemical equations are balanced?
   a. \[\text{CS}_2 + 3\text{O}_2 \rightarrow \text{CO}_2 + \text{SO}_2\]
   b. \[2\text{N}_2\text{O}_5 + \text{NO} \rightarrow 4\text{NO}_2\]
   c. \[\text{P}_4 + 5\text{O}_2 \rightarrow \text{P}_2\text{O}_5\]
   d. \[\text{Cl}_2 + 2\text{Br} \rightarrow 2\text{Cl} + \text{Br}_2\]
   e. \[\text{Na}_2\text{SO}_4 + \text{BaCl}_2 \rightarrow \text{BaSO}_4 + \text{NaCl}\]
7. Use the graph below and the “Periodic Table of the Elements on page 224 to number the elements in a through f in order of increasing energy of their nuclei.

![Graph showing energy of the nucleus vs. atomic number]

<table>
<thead>
<tr>
<th>Energy (x10^-12 J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>250</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

Atomic Number

- Carbon (C)
- Iron (Fe)
- Magnesium (Mg)
- Lithium (Li)
- Lead (Pb)
- Krypton (Kr)

8. Use the graph in question 7 and your knowledge of nuclear reactions to indicate which pairs of atomic nuclei would be most likely to release energy by fission and which would release energy by fusion.

a. Helium-4 and carbon-12
b. Uranium-235 and strontium-135
c. Carbon-12 and carbon-12

9. Radon has a half-life of 3.8 days. How long does it take for 16 grams of radon to be reduced to 2 grams of radon?

**Applying Your Knowledge**

**Section 11.1**

1. Rocks are the most common materials on Earth. The rock cycle is a group of changes that continuously recycles rocks. Research the rock cycle. Make a poster that illustrates the rock cycle. List the chemical and physical changes that rocks undergo for each phase of the cycle.

2. Around the world, over 5 million tires are discarded each day. Recycling scrap tires requires the use of physical and chemical changes. Research the recycling of scrap tires. Prepare a short report that answers the following questions:
   a. What are the challenges to recycling tires?
   b. What are the chemical and physical changes used in recycling tires?
   c. How are recycled tires used? What are the advantages and disadvantages for each use?

**Section 11.2**

3. Identify an industry in your community that uses chemical reactions. (It may be more difficult to find an industry that doesn’t use them!) Examples of industries you may consider 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 chemical equations for each reaction you identify.

4. Global warming is a concern of scientists and other citizens around the world. Conduct research to find out the major global warming gases and the chemical reactions that produce them.

**Section 11.3**

5. Research the possibility of using nuclear fusion as an energy source. Prepare a short report that answers the following questions:
   a. What are the challenges to using nuclear fusion for power?
   b. What are the advantages of using nuclear fusion for power?
   c. What is magnetic confinement fusion and how does it work?