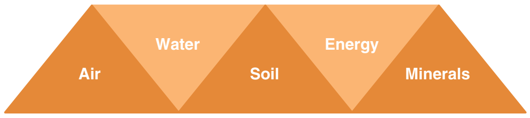
3 Science, Systems, Matter, and Energy



CASE STUDY

An Environmental Lesson from Easter Island

Easter Island (Rapa Nui) is a small, isolated island in the great expanse of the South Pacific. Polynesians used double-hulled sea-going canoes to colonize this island about 2,500 years ago. They brought along their pigs, chickens, dogs, stowaway rats, taro roots, yams, bananas, and sugarcane.

Evidence from pollen grains found in the soil and lake sediments and in artifacts shows that the island was abundantly forested with a variety of trees—including basswoods (called hauhau) and giant palms. The Polynesians developed a civilization based on the island's trees. The towering palm trees were used for shelter, tools, and fishing boats. Hauhau trees were felled and burned to cook and keep warm in the island's cool winters, and rope was made from the tree's fibers. Land was also cleared of trees to plant taro, sugarcane, bananas, and yams.

Using these abundant tree resources, the Polynesians developed an impressive civilization. They also developed a technology capable of making and moving large stone structures, including their famous statues (Figure 3-1). The people flourished, with the population peaking at somewhere between 7,000 and 20,000 by 1400. However, they used up the island's precious trees faster than they were regenerated—an example of the tragedy of the commons.

By 1600, only a few small trees were left. Without large trees, the islanders could not build their traditional big canoes for hunting porpoises and catching fish in deeper offshore waters, and no one could escape the island by boat. Without the once-great forests to absorb and slowly release water, springs and streams dried up, exposed soils eroded, crop yields plummeted, and famine struck. There was no firewood for cooking or keeping warm. The hungry islanders ate all of the island's birds. Then they began raising and eating rats, descendants of hitchhikers on the first canoes.

Both the population and the civilization collapsed as gangs fought one another for dwindling food supplies. Bone evidence indicates that the islanders began hunting and eating one another.

Dutch explorers reached the island on Easter Day, 1722, perhaps 1,000 years after the first Polynesians had landed. They found about 2,000 hungry Polynesians, living in caves on a shrubby grassland.

Like Easter Island at its peak, the earth is an isolated island in the vastness of space with no other suitable planet to migrate to. As on Easter Island, our population and resource consumption are growing and our resources are finite.

Will the humans on Earth Island re-create the tragedy of Easter Island on a grander scale, or will we learn how to live more sustainably on this planet that is our only home? Scientific knowledge is a key to learning how to live more sustainably. Thus we need to know what science is, understand the behavior of complex systems studied by scientists, and have a basic knowledge of the nature of the matter and energy that make up the earth's living and nonliving resources, as discussed in this chapter.

Figure 3-1 These massive stone figures on Easter Island are the remains of the technology created by an ancient civilization of Polynesians. Their civilization collapsed because the people used up the trees (especially large palm trees) that were the basis of their livelihood. More than 200 of these stone statues once stood on huge stone platforms lining the coast. At least 700 additional statues were found turned over, abandoned in rock quarries or on ancient roads between the quarries and the coast. No one knows how the early islanders (with no wheels, no draft animals, and no sources of energy other than their own muscles) transported these gigantic structures for miles before erecting them. We presume they accomplished it by felling large trees and using them to roll and erect the statues.

Science is an adventure of the human spirit. It is essentially an artistic enterprise, stimulated largely by curiosity, served largely by disciplined imagination, and based largely on faith in the reasonableness, order, and beauty of the universe.

WARREN WEAVER

This chapter addresses the following questions:

- What is science, and what do scientists do?
- What are major components and behaviors of complex systems?
- What are the basic forms of matter? What makes matter useful to us as a resource?
- What are the major forms of energy? What makes energy useful to us as a resource?
- What scientific law governs changes of matter from one physical or chemical form to another?
- What three main types of nuclear changes can matter undergo?
- What are two scientific laws governing changes of energy from one form to another?
- How are the scientific laws governing changes of matter and energy from one form to another related to resource use and environmental degradation?

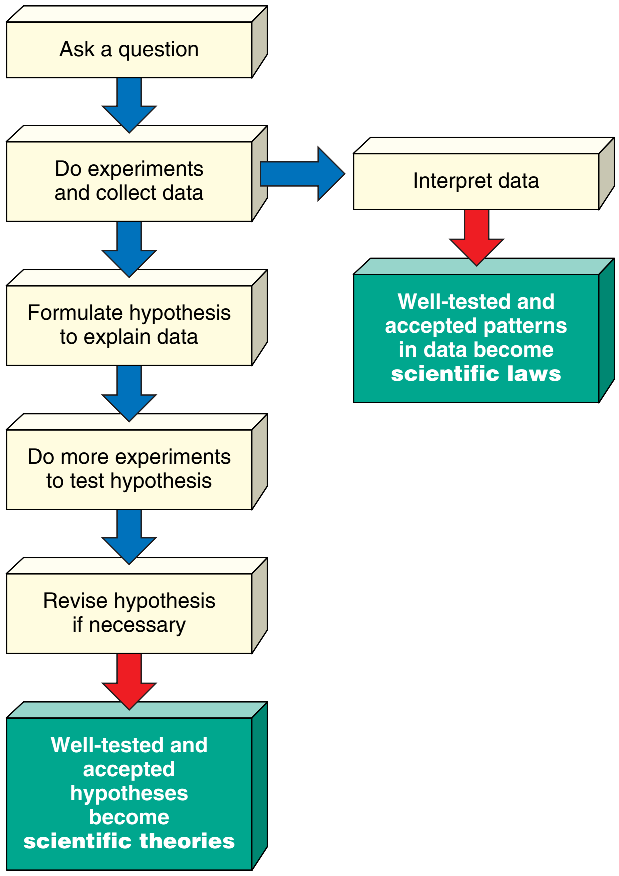


Figure 3-2 What scientists do.

3-1 THE NATURE OF SCIENCE

What Is Science and What Do Scientists Do? Searching for Order in Nature

Scientists collect data, form hypotheses, and develop theories, models, and laws about how nature works.

Science is an attempt to discover order in the natural world and use that knowledge to describe what is likely to happen in nature. Its goal is to increase our understanding of the natural world. Science is based on the fundamental assumption that events in the natural world follow orderly patterns that can be understood through careful observation and experimentation.

Figure 3-2 summarizes the scientific process. Trace the pathways in this figure.

The first thing scientists do is ask a question or identify a problem to be investigated. Then they collect **scientific data,** or facts, related to the problem or question, by making observations and measurements. They often conduct **experiments** to study some phenomenon under known conditions. The resulting scientific data or facts must be confirmed by repeated observations and measurements, ideally by several different investigators.

The primary goal of science is not the data or facts themselves. Instead science seeks new ideas, principles, or models that connect and explain certain scientific data and descriptions of what is likely to happen in nature. Scientists working on a particular problem try to come up with a variety of possible explanations, or **scientific hypotheses,** of what they (or other scientists) observe in nature. A scientific hypothesis is an unconfirmed explanation of an observed phenomenon that can be tested by further research.

One method scientists use to test a hypothesis is to develop a **model,** an approximate or simplified representation or simulation of a system being studied. It may be an actual working model, a mental model, a pictorial model, a computer model, or a mathematical model.

Three important features of the scientific process are *skepticism, reproducibility, and peer review* of results by other scientists. Scientists tend to be highly skeptical of any new data or hypotheses until they can be confirmed or verified.

Peers, or scientists working in the same field, check for reproducibility by repeating and checking out one another's work to see if the data can be reproduced and whether proposed hypotheses are reasonable and useful.

Peer review happens when scientists openly publish details of the methods they used, the results of their experiments, and the reasoning behind their hypotheses. This process of publishing one's work for other scientists to examine and criticize helps keep scientists honest and reduces bias.

If repeated observations and measurements or tests using models support a particular hypothesis or a group of related hypotheses, the hypothesis becomes a **scientific theory.** In other words, a *scientific theory* is a verified, credible, and widely accepted scientific hypothesis or a related group of scientific hypotheses.

To scientists, scientific theories are not to be taken lightly. They are not guesses, speculations, or suggestions. Instead, they are useful explanations of processes or natural phenomena that have a high degree of certainty because they are supported by extensive evidence.

New evidence or a better explanation may modify, or in rare cases overturn, a particular scientific theory. But unless or until this happens, a scientific theory is the best and most reliable knowledge we have about how nature works.

Nonscientists often use the word *theory* incorrectly when they mean to refer to a *scientific hypothesis,* a tentative explanation or educated guess that needs further evaluation. The statement, "Oh, that's just a theory," made in everyday conversation, implies a lack of knowledge and careful testing—the opposite of the scientific meaning of the word.

Another important result of science is a **scientific,** or **natural, law:** a description of what we find happening in nature over and over in the same way. For example, after making thousands of observations and measurements over many decades, scientists formulated the *second law of thermodynamics.* Simply stated, this law says that heat always flows spontaneously from hot to cold—something you learned the first time you touched a hot object. A scientific law is no better than the accuracy of the observations or measurements upon which it is based. But if the data are accurate, a scientific law cannot be broken.

How Do Scientists Learn about Nature? Follow Many Paths

There are many scientific methods.

We often hear about *the* scientific method. In reality, many **scientific methods** exist: they are ways in which scientists gather data and formulate and test scientific hypotheses, models, theories, and laws.

Here is an example of applying the scientific process to an everyday situation:

Observation: You switch on your trusty flashlight and nothing happens.

Question: Why did the light not come on?

Hypothesis: Maybe the batteries are bad.

Test the hypothesis: Put in new batteries and switch on the flashlight .

Result: Flashlight still does not work.

New hypothesis: Maybe the bulb is burned out.

Experiment: Replace bulb with a new bulb.

Result: Flashlight works when switched on.

Conclusion: Second hypothesis is verified.

Situations in nature are usually much more complicated than this. Many *variables* or *factors* influence most processes or parts of nature that scientists seek to understand. Ideally, scientists conduct a *controlled experiment* to isolate and study the effect of a single variable. To do such *single-variable analysis,* scientists set up two groups. One is an *experimental group* in which the chosen variable is changed in a known way. The other is a *control group* in which the chosen variable is not changed. If the experiment is designed properly, any difference between the two groups should result from the variable that was changed in the experimental group (see Connections, right).

A basic problem is that many of the problems environmental scientists investigate involve a huge number of interacting variables. This limitation is sometimes overcome by using *multivariable analysis*—running mathematical models on high-speed computers to analyze the interactions of many variables without having to carry out traditional controlled experiments.

What Types of Reasoning Do Scientists Use? Bottom-Up and Top-Down Reasoning

Scientists use inductive reasoning to convert observations and measurements to a general conclusion and deductive reasoning to convert a generalization to a specific conclusion.

Scientists arrive at certain conclusions with varying degrees of certainty by using inductive and deductive reasoning. **Inductive reasoning** involves using specific observations and measurements to arrive at a general conclusion or hypothesis. It is a form of *"bottom-up" reasoning* that involves going from the specific to the general. For example, suppose we observe that a variety of different objects fall to the ground when we drop them from various heights. We might then use inductive reasoning to conclude that *all objects fall to the earth's surface when dropped.* Depending on the number of observations made, there may be a high degree of certainty in this conclusion. However, what we are really saying is that "All objects that we or other observers have dropped from various heights fall to the earth's surface." Although it is extremely unlikely, we

CONNECTIONS

What Is Harming the Robins?

Suppose a scientist observes an abnormality in the growth of robin embryos in a certain area. She knows the area has been sprayed with a pesticide and suspects the chemical may be causing the abnormalities she has observed.

To test this hypothesis, the scientist carries out a *controlled experiment.* She maintains two groups of robin embryos of the same age in the laboratory. Each group is exposed to exactly the same conditions of light, temperature, food supply, and so on, except the embryos in the experimental group are exposed to a known amount of the pesticide in question.

The embryos in both groups are then examined over an identical period of time for the abnormality. If she finds a significantly larger number of the abnormalities in the experimental group than in the control group, the results support the idea that the pesticide is the culprit.

To be sure no errors occur during the procedure, the original researcher should repeat the experiment several times. Ideally one or more other scientists should repeat the experiment independently.

Critical Thinking

Can you find flaws in this experiment that might lead you to question the scientist's conclusions? (*Hint:* What other factors in nature—not the laboratory—and in the embryos themselves could possibly explain the results?)

cannot be *absolutely sure* someone will drop an object that does not fall to the earth's surface.

Deductive reasoning involves using logic to arrive at a specific conclusion based on a generalization or premise. It is a form of *"top-down"* reasoning that goes from the general to the specific. For example,

Generalization or premise: All birds have feathers.

Example: Eagles are birds.

Deductive conclusion: All eagles have feathers.

The conclusion of this *syllogism* (a series of logically connected statements) is valid as long as the premise is correct and we do not use faulty logic to arrive at the conclusion.

Deductive and inductive reasoning and critical thinking skills (p. 3) are important scientific tools. But scientists also try to come up with new or creative ideas to explain some of the things they observe in nature. Often such ideas defy conventional logic and current scientific knowledge. According to physicist Albert Einstein, "There is no completely logical way to a new scientific idea." Intuition, imagination, and creativity are as important in science as they are in poetry, art, music, and other great adventures of the human spirit, as reflected in scientist Warren Weaver's quotation found at the opening of this chapter.

One of the exciting things about science is that it is never complete. Each discovery unearths new unanswered questions in an ongoing quest for knowledge about how the natural world works. This is one reason why people choose this profession.

How Valid Are the Results of Science? Very Reliable But Not Perfect

Scientists try to establish that a particular model, theory, or law has a very high probability of being true.

Scientists can do two major things. *First,* they can disprove things. *Second,* they can establish that a particular model, theory, or law has a very high probability or degree of certainty of being true. However, like scholars in any field, scientists cannot prove that their theories, models, and laws are *absolutely true.*

Although it may be extremely low, some degree of uncertainty is always involved in any scientific theory, model, or law. Most scientists rarely say something like, "Cigarettes cause lung cancer." Rather, the statement might be phrased, "There is overwhelming evidence from thousands of studies that indicate a significant relationship between cigarette smoking and lung cancer."

Most scientists also rarely use the word *proof.* When scientists hear someone say we should not take a scientific finding seriously because it has not been absolutely proven they know that this person either knows little about the nature of science or is using a debating or advertising trick to cast doubt on a widely accepted scientific finding. Scientists tend to use words like *projections* and *scenarios* to describe what is *likely* to happen in nature instead of making *predictions* or *forecasts* about what *will* happen.

What Is the Difference between Frontier Science and Sound Science? Preliminary and Well-Tested Results

Scientific results fall into those that have not been confirmed (frontier science) and those that have been well tested and widely accepted (sound science).

News reports about science often focus on two things: new so-called scientific breakthroughs, and disputes between scientists over the validity of preliminary and untested data, hypotheses, and models. These preliminary results, called **frontier science,** are often controversial because they have not been widely tested and accepted. At the frontier stage, it is normal and healthy for reputable scientists to disagree about the meaning and accuracy of data and the validity of various hypotheses.

By contrast, **sound science,** or **consensus science,** consists of data, theories, and laws that are widely accepted by scientists who are considered experts in the field involved. The results of sound science are based on a self-correcting process of open peer review. One way to find out what scientists generally agree on is to seek out reports by scientific bodies such as the U.S. National Academy of Sciences and the British Royal Society, which attempt to summarize consensus among experts in key areas of science.

What Is Junk Science and How Can We Detect It? Look Out for Baloney

Junk science is untested ideas presented as sound science.

Junk science consists of scientific results or hypotheses presented as sound science but not having undergone the rigors of the peer review process. Note that frontier science is not necessarily junk science. Instead, it represents tentative results or hypotheses that are in the process of being validated or rejected by peer review.

There are two problems in uncovering junk science. One is that some scientists, politicians, and other analysts label as junk science any science that does not support or further their particular agenda. The other is that reporters and journalists sometimes mislead us in presenting sound or consensus science along with a quote from a scientist in the field who disagrees with the consensus view or from one who is not an expert in the field being discussed. Such attempts to give a false sense of balance or fairness can mislead the public into distrusting well-established sound science.

Here are some critical thinking questions you can use to uncover junk science.

- How reliable are the sources making a particular claim? Do they have a hidden agenda? Are they experts in this field? What is their source of funding?
- Do the conclusions follow logically from the observations?
- Has the claim been verified by impartial peer review?
- How does the claim compare with the consensus view of experts in this field?

3-2 MODELS AND BEHAVIOR OF SYSTEMS

Why Are Models of Complex Systems Useful? Using Inputs, Throughputs, and Outputs to Make Projections

Scientists project the behavior of a complex system by developing a model of its inputs, throughputs (flows), and outputs of matter, energy, and information.

A **system** is a set of components that function and interact in some regular and theoretically understandable manner. Most *systems* have the following key components: **inputs** from the environment, **flows** or **throughputs** within the system at certain rates, and **outputs** to the environment (Figure 3-3).

Scientists use *models* or approximate representations or simulations to find out how systems work and to evaluate ideas or hypotheses. Some of the most powerful and useful technologies invented by humans are mathematical models, which are used to supplement our mental models. *Mathematical models* consist of one or more equations used to describe the behavior of a system and to describe how the system is likely to behave.

Making a mathematical model usually requires going many times through three steps. *First,* make a guess and write down some equations. *Second,* compute the likely behavior of the system implied by the equations. *Third,* compare the system's projected behavior with observations and behavior projected by mental models, existing experimental data, and scientific hypotheses, laws, and theories.

Mathematical models are important because they can give us improved perceptions and projections, especially in situations where our mental models are weak and unreliable. They are particularly useful when there are many interacting variables, when the time frame is long, and when controlled experiments are impossible, too slow, or too expensive to conduct.

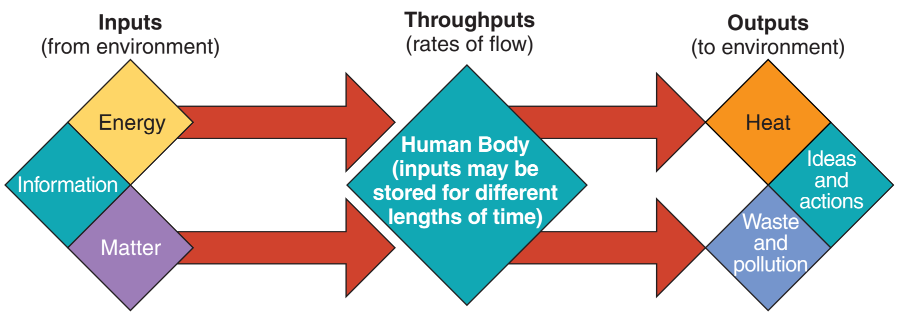


Figure 3-3 Major components of a *system* such as your body.

After building and testing a mathematical model, scientists use it to project what is *likely* to happen under a variety of conditions. In effect, they use mathematical models to answer *if–then* questions: "*If* we do such and such, *then* what is likely to happen now and in the future?" This process can give us a variety of projections or scenarios of possible futures or outcomes based on different assumptions.

Despite its usefulness, a mathematical model is nothing more than a set of hypotheses or assumptions about how we think a certain system works. Mathematical models (like all other models) are no better than the assumptions on which they are built and the data fed into them.

How Do Feedback Loops Affect Systems? Changing Direction

Outputs of matter, energy, or information fed back into a system can cause the system to do more of what it was doing (positive feedback) or less (negative feedback).

When someone asks you for feedback, they are asking for information that they can feed back into their mental processes to help them make a decision or carry out some action. All systems undergo change as a result of feedback loops. A **feedback loop** occurs when an output of matter, energy, or information is fed back into the system as an input and leads to changes in that system.

A **positive feedback loop** causes a system to change further in the same direction. One example involves depositing money in a bank at compound interest and leaving it there. The interest increases the balance, which through a positive feedback loop leads to more interest and an even higher balance.

A **negative,** or **corrective, feedback loop** causes a system to change in the opposite direction. An example is recycling aluminum cans. This involves melting aluminum and feeding it back into an economic system to make new aluminum products. This negative feedback loop of matter reduces the need to find, extract, and process virgin aluminum ore. It also reduces the flow of waste matter (discarded aluminum cans) into the environment.

The temperature-regulating system of your body is an example of a system governed by feedback. Normally a negative feedback loop prevents your body temperature from going too high. If you get hot, your brain receives this information and causes your body to sweat. The evaporation of sweat on your skin removes heat and cools your body. However, if your body temperature exceeds 42°C (108°F), your temperature control system breaks down as your body produces more heat than your sweat-dampened skin can get rid of. Then a positive feedback loop caused by overloading the system overwhelms the negative feedback loop. These conditions produce a net gain in body heat, which produces even more body heat, and so on, until you die from heatstroke.

The tragedy on Easter Island discussed at the beginning of the chapter also involved the coupling of positive and negative feedback loops. As the abundance of trees turned to a shortage of trees, a positive feedback loop (more births than deaths) became weaker as death rates rose. Eventually a negative feedback loop (more deaths than births) dominated and caused a dieback of the island's human population.

How Do Time Delays Affect Complex Systems? Waiting for Something to Kick In

Sometimes corrective feedback takes so long to work that a system can cross a threshold and change its normal behavior.

Complex systems often show **time delays** between the input of a stimulus and the response to it. A long time delay can mean that corrective action comes too late. For example, a smoker exposed to cancer-causing chemicals in cigarette smoke may not get lung cancer for 20 years or more.

Time delays allow a problem to build up slowly until it reaches a *threshold level* and causes a fundamental shift in the behavior of a system. Prolonged delays dampen the negative feedback mechanisms that might slow, prevent, or halt environmental problems. Examples are population growth, leaks from toxic waste dumps, and degradation of forests from prolonged exposure to air pollutants.

What Is Synergy, and How Can It Affect Complex Systems? One Plus One Can Be Greater Than Two

Sometimes processes and feedbacks in a system can interact to amplify the results.

In arithmetic, 1 plus 1 always equals 2. However, in some of the complex systems found in nature, 1 plus 1 may add up to more than 2 because of synergistic interactions. A **synergistic interaction,** or **synergy,** occurs when two or more processes interact so that the combined effect is greater than the sum of their separate effects.

Synergy can result when two people work together to accomplish a task. For example, suppose you and I need to move a 140-kilogram (300-pound) tree that has fallen across the road. By ourselves, each of us can lift only, say, 45 kilograms (100 pounds). But if we work together and use our muscles properly, we can move the tree out of the way. That is using synergy to solve a problem. Research in the social sciences suggests that most political changes or changes in cultural beliefs are brought about by only about 5% (and rarely more than 10%) of a population working together (synergizing) and expanding their efforts to influence other people.

How Can We Anticipate Environmental Surprises? We Can Never Do Just One Thing

Because any action in a complex system has multiple and often unpredictable results, we should try to anticipate and plan for unintended results and surprises.

One basic principle of environmental science is *we can never do just one thing*. Any action in a complex system has multiple, unintended, and often unpredictable effects. Indeed, most of the harmful environmental problems we face today are unintended results of activities designed to increase the quality of human life (Figure 3-4).

One factor that can lead to an environmental surprise is a *discontinuity* or abrupt change in a previously stable system when some *environmental threshold* is crossed. For example, you may be able to lean back in a chair and balance yourself on two of its legs for a long time with only minor adjustments. But if you pass a certain threshold of movement, your balanced system suffers a discontinuity, or sudden shift, and you may find yourself on the floor. A similar change can happen when many trees in a forest start dying after being weakened and depleted of soil nutrients after decades of exposure to a cocktail of air pollutants.

3-3 MATTER

What Types of Matter Do We Find in Nature? Getting to the Bottom of Things

Matter exists in chemical forms as elements and compounds.

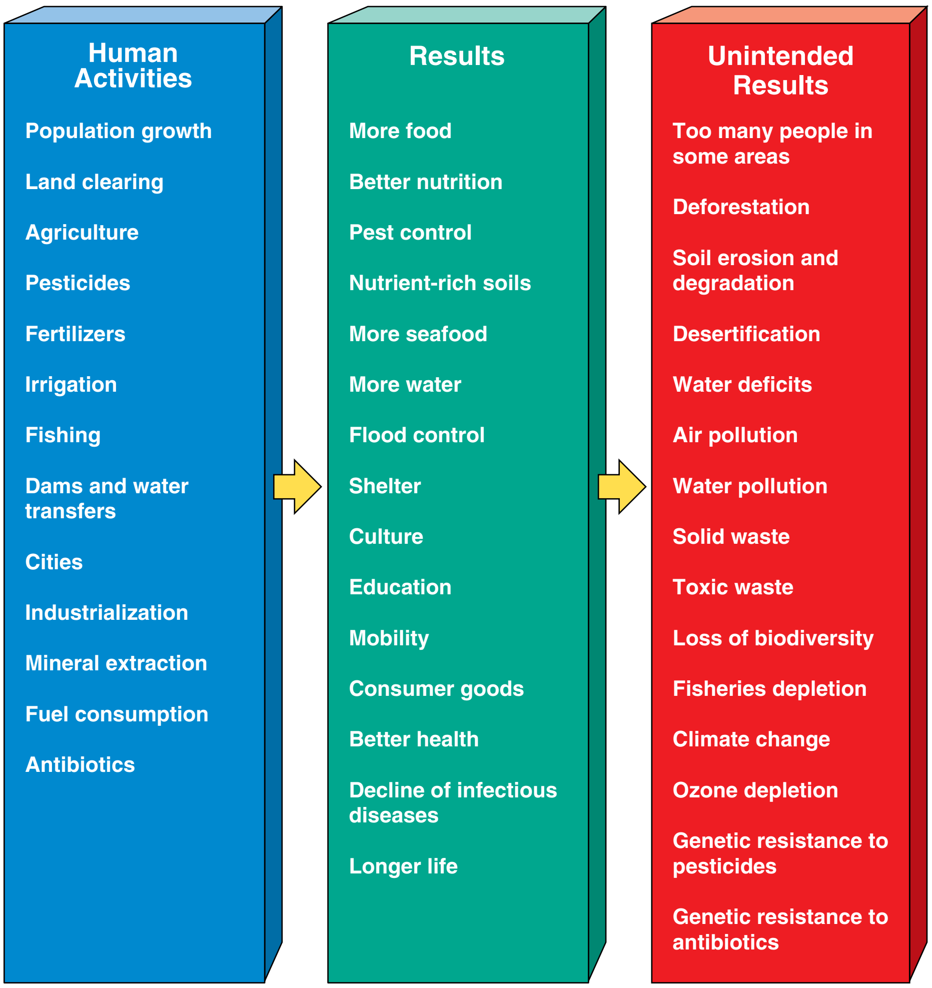


Figure 3-4 **Natural capital degradation:** human activities designed to improve the quality of life have had a number of unintended harmful environmental effects.

I am going to give you a brief introduction to some chemistry—a discussion of matter and energy. Some of you are saying "I hate chemistry. Why do I need to know this stuff?" The answer is that you and every other material thing on this planet are made up of chemicals and energy. To understand life and environmental problems, you need to know a wee bit of chemistry. I will try to make this journey as interesting and painless as possible. For those of you who have had some basic chemistry, this material will be a breeze.

Matter is anything that has mass (the amount of material in an object) and takes up space. Matter is found in two chemical forms. One is **elements**: the distinctive building blocks of matter that make up every material substance. The other consists of **compounds**: two or more different elements held together in fixed proportions by attractive forces called *chemical bonds.*

To simplify things, chemists represent each element by a one- or two-letter symbol. Examples used in this book are hydrogen (H), carbon (C), oxygen (O), nitrogen (N), phosphorus (P), sulfur (S), chlorine (Cl), fluorine (F), bromine (Br), sodium (Na), calcium (Ca), lead (Pb), mercury (Hg), arsenic (As), and uranium (U). Chemists have developed a way to classify elements in terms of their chemical behavior by arranging them in a *periodic table of elements,* as discussed in Appendix 3. *Good news.* The elements in the list above are the only ones you need to know to understand the material in this book.

From a chemical standpoint, how much are you worth? Not much. If we add up the market price per kilogram for each element in someone weighing 70 kilograms (154 pounds), the total value comes to about $120. Not very uplifting, is it?

But of course you are worth much more because your body is not just a bunch of chemicals enclosed in a bag of skin. Instead you are an incredibly complex system of air, water, soil nutrients, energy-storing chemicals, and food chemicals interacting in millions of ways to keep you alive and healthy. Feel better now?

What Are Nature's Building Blocks? Matter's Bricks

Atoms, ions, and molecules are the building blocks of matter.

If you had a supermicroscope capable of looking at individual elements and compounds, you could see they are made up of three types of building blocks. The first is an **atom:** the smallest unit of matter that exhibits the characteristics of an element. The second is an **ion:** an electrically charged atom or combination of atoms. A third building block is a **molecule:** a combination of two or more atoms of the same or different elements held together by chemical bonds.

Some elements are found in nature as molecules. Examples are nitrogen and oxygen, which together make up about 99% of the volume of air you just inhaled. Two atoms of nitrogen (N) combine to form a gaseous molecule, with the shorthand formula N_2 (read as "N-two"). The subscript after the element's symbol indicates the number of atoms of that element in a molecule. Similarly, most of the oxygen gas in the atmosphere exists as O_2 (read as "O-two") molecules. A small amount of oxygen, found mostly in the second layer of the atmosphere (stratosphere), exists as O_3 (read as "O-three") molecules, a gaseous form of oxygen called *ozone.*

What Are Atoms Made Of? Looking Inside

Each atom has a tiny nucleus containing protons, and in most cases neutrons, and one or more electrons whizzing around somewhere outside the nucleus.

If you increased the magnification of your supermicroscope, you would find that each different type of atom contains a certain number of *subatomic particles.* There are three types of these atomic building blocks: positively charged **protons** (p), uncharged **neutrons** (n), and negatively charged **electrons** (e). Actually, there are other particles, but they need not concern us at this introductory level.

Each atom consists of an extremely small center, or **nucleus.** It contains one or more protons, and in most cases neutrons, and one or more electrons in rapid motion somewhere outside the nucleus. Atoms are incredibly small. More than 3 million hydrogen atoms could sit side by side on the period at the end of this sentence. Now that is tiny.

Each atom has a certain number of positively charged protons inside its nucleus and an equal number of negatively charged electrons outside its nucleus. Because these electrical charges cancel one another, *the atom as a whole has no net electrical charge.*

Each element has its own specific **atomic number,** equal to the number of protons in the nucleus of each of its atoms. The simplest element, hydrogen (H), has only 1 proton in its nucleus, so its atomic number is 1. Carbon (C), with 6 protons, has an atomic number of 6. Uranium (U), a much larger atom, has 92 protons and an atomic number of 92.

Because atoms are electrically neutral, the atomic number of an atom tells us the number of positively charged protons in its nucleus and the equal number of negatively charged electrons outside its nucleus. For example, an atom of uranium with an atomic number of 92 has 92 protons in its nucleus and 92 electrons outside, and thus no net electrical charge.

Because electrons have so little mass compared with the mass of a proton or a neutron, *most of an*

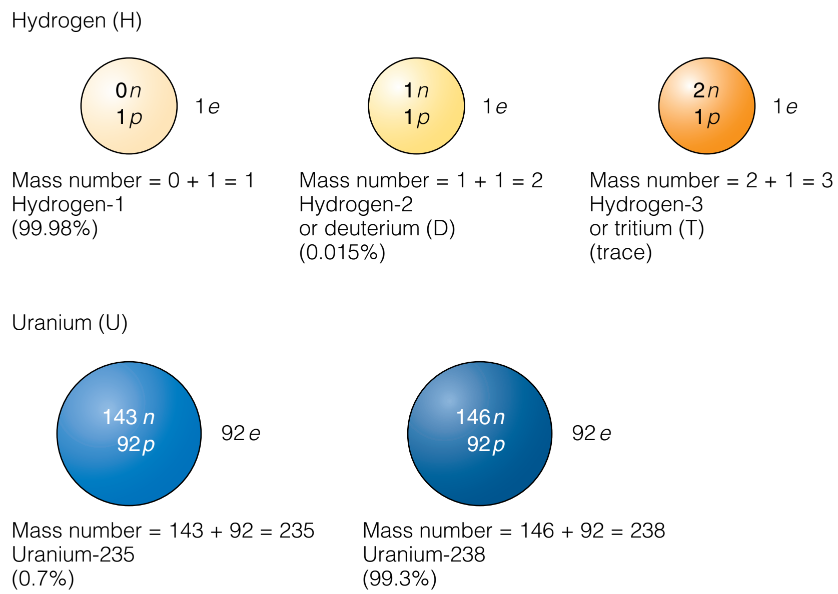


Figure 3-5 Isotopes of hydrogen and uranium. All isotopes of hydrogen have an atomic number of 1 because each has one proton in its nucleus; similarly, all uranium isotopes have an atomic number of 92. However, each isotope of these elements has a different mass number because its nucleus contains a different number of neutrons. Figures in parentheses indicate the percentage abundance by weight of each isotope in a natural sample of the element.

atom's mass is concentrated in its nucleus. The mass of an atom is described in terms of its **mass number:** the total number of neutrons and protons in its nucleus. For example, a hydrogen atom with 1 proton and no neutrons in its nucleus has a mass number of 1, and an atom of uranium with 92 protons and 143 neutrons in its nucleus has a mass number of 235 (92 + 143 = 235).

All atoms of an element have the same number of protons in their nuclei. But they may have different numbers of uncharged neutrons in their nuclei, and thus may have different mass numbers. Various forms of an element having the same atomic number but a different mass number are called **isotopes** of that element. Scientists identify isotopes by attaching their mass numbers to the name or symbol of the element. For example, hydrogen has three isotopes: hydrogen-1 (H-1), hydrogen-2 (H-2, common name *deuterium*), and hydrogen-3 (H-3, common name *tritium*). A natural sample of an element contains a mixture of its isotopes in a fixed proportion, or percentage abundance by weight (Figure 3-5).

What Are Ions? Getting Charged Up

Atoms of some elements can lose or gain one or more electrons to form ions with positive or negative electrical charges.

Ions form when an atom of an element loses or gains one or more electrons. Thus an *ion* is an atom or groups of atoms with one or more net positive (+) or negative (−) electrical charges, one for each electron lost or gained. Atoms are neutral but ions are all charged up.

Some elements, known as *metals,* tend to lose one or more of their electrons and form positively charged ions. Like a quarterback passing a football, they are *electron givers.* For example, an atom of the metallic element sodium (Na, atomic number 11) with 11 positively charged protons and 11 negatively charged electrons can lose one of its electrons. It then becomes a sodium ion with a positive charge of 1 (Na^+) because it now has 11 positive charges (protons) but only 10 negative charges (electrons).

Other atoms, known as *nonmetals,* tend to gain one or more electrons and form negatively charged ions. Like a tight end waiting for a pass from a quarterback, they are *electron receivers.* For example, an atom of the nonmetallic element chlorine (Cl, with an atomic number of 17) can gain an electron and become a chlorine ion. The ion has a negative charge of 1 (Cl^-) because it has 17 positively charged protons and 18 negatively charged electrons.

The number of positive or negative charges on an ion is shown as a superscript after the symbol for an atom or a group of atoms. Examples of ions encountered in this book are positive ions such as hydrogen ions (H^+), calcium ions (Ca^{2+}), and ammonium ions (NH_4^+), and negative ions such as nitrate ions (NO_3^-), sulfate ions (SO_4^{2-}), and phosphate ions (PO_4^{3-}).

The amount of a substance in a unit volume of air, water, or other medium is called its **concentration.** It is like the number of people in a classroom or a swimming pool.

The concentration of hydrogen ions (H^+) in a water solution is a measure of its acidity or alkalinity, represented by a value called **pH.** On a *pH scale* of 0 to 14, *acids* have a pH less than 7, *bases* have a pH greater than 7, and a *neutral solution* has a pH of 7 (Figure 3-6).

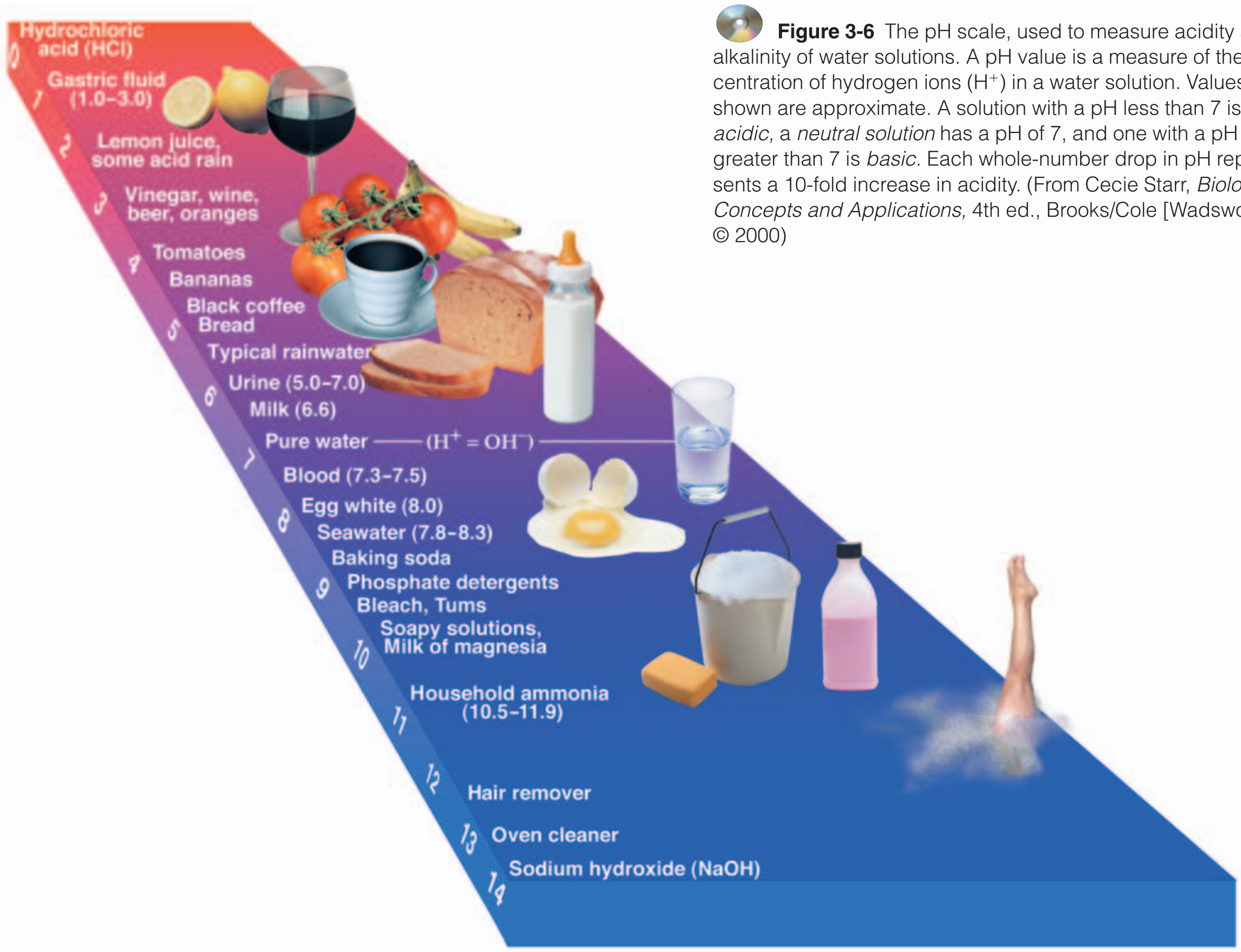


Figure 3-6 The pH scale, used to measure acidity and alkalinity of water solutions. A pH value is a measure of the concentration of hydrogen ions (H^+) in a water solution. Values shown are approximate. A solution with a pH less than 7 is *acidic*, a *neutral solution* has a pH of 7, and one with a pH greater than 7 is *basic.* Each whole-number drop in pH represents a 10-fold increase in acidity. (From Cecie Starr, *Biology: Concepts and Applications*, 4th ed., Brooks/Cole [Wadsworth] © 2000)

What Holds the Atoms and Ions in Compounds Together? Giving, Receiving, and Sharing Electrons

Some compounds are made up of oppositely charged ions and others are made up of molecules.

Most matter exists as *compounds,* substances containing atoms or ions of more than one element that are held together by chemical bonds. Chemists use a shorthand **chemical formula** to show the number of atoms or ions of each type in a compound. The formula contains the symbols for each of the elements present and uses subscripts to represent the number of atoms or ions of each element in the compound's basic structural unit.

Some compounds are made up of oppositely charged ions and are called *ionic compounds.* Those made up of molecules of uncharged atoms are called *covalent* or *molecular compounds.*

Sodium chloride (table salt) is an *ionic compound* represented by the chemical formula NaCl. It consists of a three-dimensional array of oppositely charged *ions* (Na^+ and Cl^-). The forces of attraction between these oppositely charged ions are called *ionic bonds,* as discussed in more detail in Appendix 3. They are formed when a metal atom (a giver) gives one or more electrons to a nonmetal atom (a receiver). Then the resulting positively and negatively charged ions attract one another. The result of this electron dating game, involving giving, receiving, and attraction between opposites, is an ionic compound.

Water, a *covalent* or *molecular compound,* consists of molecules made up of uncharged atoms of hydrogen (H) and oxygen (O). Each water molecule consists of two hydrogen atoms chemically bonded to an oxygen atom, yielding H_2O (read as "H-two-O") molecules. The bonds between the atoms in such molecules are called *covalent bonds,* as discussed in Appendix 3. Covalent compounds form when atoms of various elements share one or more electrons. It is electron dating by sharing.

What Are Organic Compounds? Think Carbon

Organic compounds contain carbon atoms combined with one another and with various other atoms such as hydrogen, nitrogen, or chlorine.

Table sugar, vitamins, plastics, aspirin, penicillin, and most of the chemicals in your body are **organic compounds.** If you could view these compounds with your supermicroscope, you would see that all (except one) have at least two carbon atoms (some have thousands) combined with each other and with atoms of one or more other elements such as hydrogen, oxygen, nitrogen, sulfur, phosphorus, chlorine, and fluorine. One exception, methane (CH_4), has only one carbon atom.

Almost all organic compounds are molecular compounds held together by covalent bonds. Organic compounds can be either *natural* (such as carbohydrates, proteins, and fats in natural foods) or *synthetic* (such as plastics and many drugs made by humans).

The millions of known organic (carbon-based) compounds include the following:

- *Hydrocarbons:* compounds of carbon and hydrogen atoms. An example is methane (CH_4), the main component of natural gas, and the simplest organic compound.
- *Chlorinated hydrocarbons:* compounds of carbon, hydrogen, and chlorine atoms. An example is the insecticide DDT ($C_{14}H_9Cl_5$).
- *Simple carbohydrates* (simple sugars): certain types of compounds of carbon, hydrogen, and oxygen atoms. An example is glucose ($C_6H_{12}O_6$), which most plants and animals break down in their cells to obtain energy.

What Are Genes, Chromosomes, and DNA Molecules? Linking Up Molecules

Simple organic molecules can link together to form more complex organic compounds.

Larger and more complex organic compounds, called *polymers,* consist of a number of basic structural or molecular units (*monomers*) linked by chemical bonds, somewhat like cars linked in a freight train. The three major types of organic polymers are *complex carbohydrates* consisting of two or more monomers of simple sugars (such as glucose) linked together, *proteins* formed by linking together monomers of amino acids, and *nucleic acids* (such as DNA and RNA) made by linked sequences of monomers called nucleotides, as discussed in Appendix 3.

Genes consist of specific sequences of nucleotides in a DNA molecule. Each gene carries codes (each consisting of three nucleotides) needed to make various proteins. These coded units of genetic information about specific traits are passed on from parents to offspring during reproduction.

Chromosomes are combinations of genes that make up a single DNA molecule, together with a number of proteins. Each chromosome typically contains thousands of genes. Genetic information coded in your chromosomal DNA is what makes you different from an oak leaf, an alligator, or a flea and from your parents. The relationships of genetic material to cells are depicted in Figure 3-7, which you may find useful in getting genetic terms straight.

The total weight of the DNA needed to reproduce the world's 6.4 billion people is only about 50 milligrams—the weight of a small match. If the DNA coiled in your body were unwound, it would stretch about 960 million kilometers (600 million miles)—more than six times the distance between the sun and the earth.

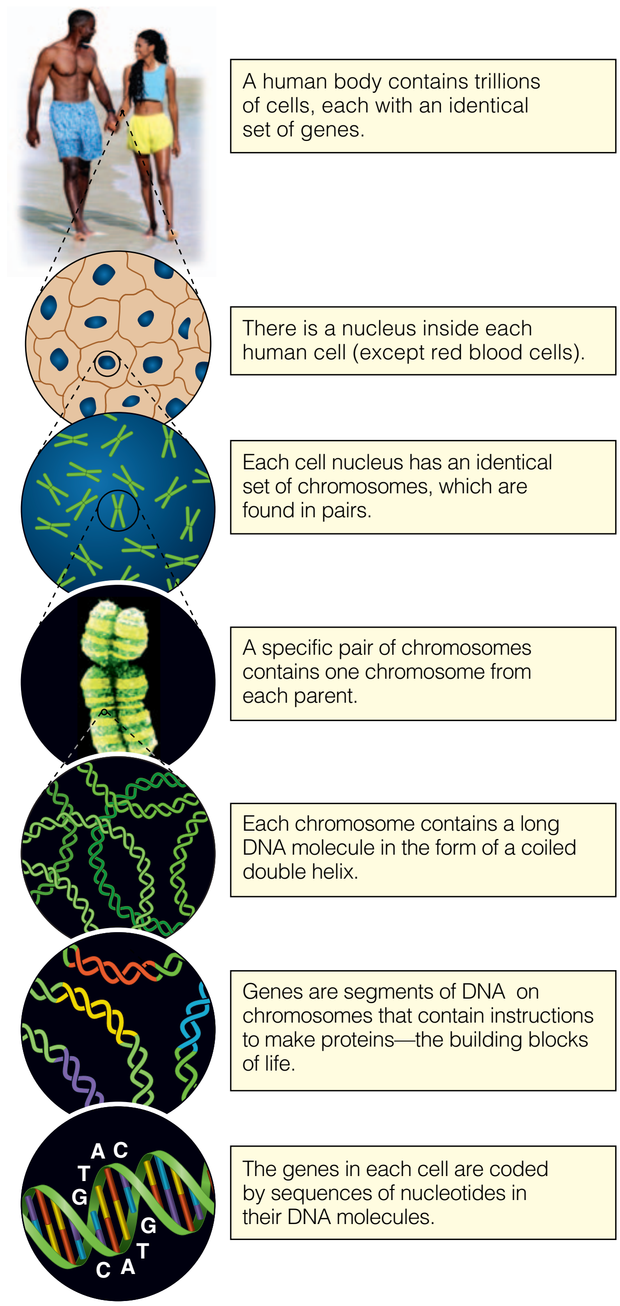


Figure 3-7 Relationships among cells, nuclei, chromosomes, DNA, genes, and nucleotides.

The different molecules of DNA that make up the millions of species found on the earth are like a vast and diverse genetic library. Each species is a unique book in that library.

The *genome* of a species is made up of the entire sequence of DNA "letters" or base pairs that combine to "spell out" the chromosomes in typical members of each species. In 2002, scientists were able to map out the genome for the human species.

What Are Inorganic Compounds? The Rest of the World's Compounds

Compounds without carbon–carbon and carbon–hydrogen bonds are called inorganic compounds.

Inorganic compounds do not have carbon–carbon or carbon–hydrogen bonds. Some of the inorganic compounds discussed in this book are sodium chloride (NaCl), water (H_2O), nitrous oxide (N_2O), nitric oxide (NO), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ammonia (NH_3), hydrogen sulfide (H_2S), sulfuric acid (H_2SO_4), and nitric acid (HNO_3). *Good news.* These are the only inorganic compounds you need to know to understand the material in this book.

Now you know about the fairly small cast of chemicals (atoms, ions, molecules, and compounds) you will encounter in this book.

What Are Four States of Matter? Let's Get Physical

Matter exists in solid, liquid, and gaseous physical states and a fourth state known as plasma.

The atoms, ions, and molecules that make up matter are found in three *physical states:* solid, liquid, and gas. For example, water exists as ice, liquid water, or water vapor depending on its temperature and the surrounding air pressure. The three physical states of any sample of matter differ in the spacing and orderliness of its atoms, ions, or molecules. A solid has the most compact and orderly arrangement and a gas the least compact and orderly arrangement. Liquids are somewhere in between.

A fourth state of matter is called **plasma.** It is a high-energy mixture of roughly equal numbers of positively charged ions and negatively charged electrons. A plasma forms when enough energy is applied to strip electrons away from the nuclei of atoms—somewhat like a blast of wind blowing the leaves off a tree.

Plasma is the most abundant form of matter in the universe. The sun and all stars consist mostly of plasma. There is little natural plasma on the earth, with most of it found in lightning bolts and flames.

But scientists have learned how to make artificial plasmas in fluorescent lights, arc lamps, neon signs, gas discharge lasers, and in TV and computer screens. They do this by running a high-voltage electric current through a gas. Scientists hope to be able to develop affordable plasma torches and use them to destroy toxic wastes, sterilize and clean water, remove soot from exhaust gases, and produce clean-burning hydrogen gas from diesel fuel, gasoline, or methane for use in fuel cells. Great stuff if we can do it.

What Is Matter Quality? Matter Usefulness

Matter can be classified as having high or low quality depending on how useful it is to us as a resource.

Matter quality is a measure of how useful a form of matter is to us as a resource, based on its availability and concentration, as shown in Figure 3-8. **High-quality**

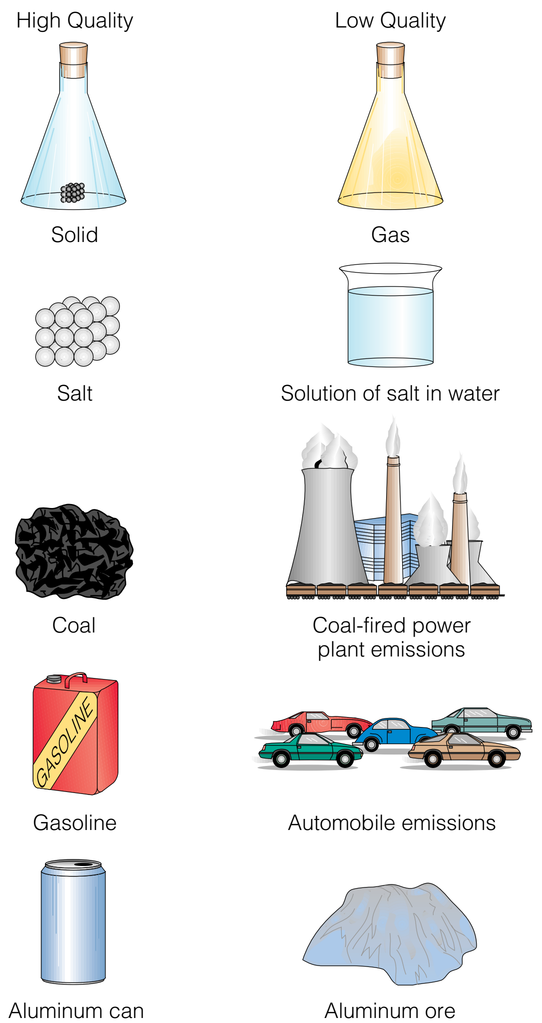


Figure 3-8 Examples of differences in matter quality. *High-quality matter* (left-hand column) is fairly easy to extract and concentrated; *low-quality matter* (right-hand column) is more difficult to extract and more dispersed than high-quality matter.

matter is concentrated, usually is found near the earth's surface, and has great potential for use as a matter resource. **Low-quality matter** is dilute, often is deep underground or dispersed in the ocean or the atmosphere, and usually has little potential for use as a material resource.

An aluminum can is a more concentrated, higher-quality form of aluminum than aluminum ore containing the same amount of aluminum. That is why it takes less energy, water, and money to recycle an aluminum can than to make a new can from aluminum ore.

Material efficiency, or **resource productivity,** is the total amount of material needed to produce each unit of goods or services. *Great news.* Business expert Paul Hawken and physicist Amory Lovins contend that resource productivity in developed countries could be improved by 75–90% within two decades using existing technologies.

3-4 ENERGY

What Is Energy? Doing Work and Transferring Heat

Energy is the work needed to move matter and the heat that flows from hot to cooler samples of matter.

Energy is the capacity to do work and transfer heat. Work is performed when an object such as a grain of sand, this book, or a giant boulder is moved over some distance. Work, or matter movement, also is needed to boil water or burn natural gas to heat a house or cook food. Energy is also the heat that flows automatically from a hot object to a cold object when they come in contact.

There are two major types of energy. One is **kinetic energy,** possessed by matter because of the matter's mass and its speed or velocity. Examples of this energy in motion are wind (a moving mass of air), flowing streams, heat flowing from a body at a high temperature to one at a lower temperature, and electricity (flowing electrons).

The second type is **potential energy,** which is stored and potentially available for use. Examples of this stored energy are a rock held in your hand, an unlit match, still water behind a dam, the chemical energy stored in gasoline molecules, and the nuclear energy stored in the nuclei of atoms.

Potential energy can be changed to kinetic energy. Drop a rock or this book on your foot and the book's potential energy when you held it changes into kinetic energy. When you burn gasoline in a car engine, the potential energy stored in the chemical bonds of its molecules changes into heat, light, and mechanical (kinetic) energy that propel the car.

What Is Electromagnetic Radiation? Think Waves

Some energy travels in waves at the speed of light.

Another type of energy is **electromagnetic radiation.** It is energy traveling in the form of a *wave* as a result of changing electric and magnetic fields.

There are many different forms of electromagnetic radiation, each with a different *wavelength* (distance between successive peaks or troughs in the wave) and *energy content,* as shown in Figure 3-9. Such radiation travels through space at the speed of light, which is about 300,000 kilometers (186,000 miles) per second. That is fast.

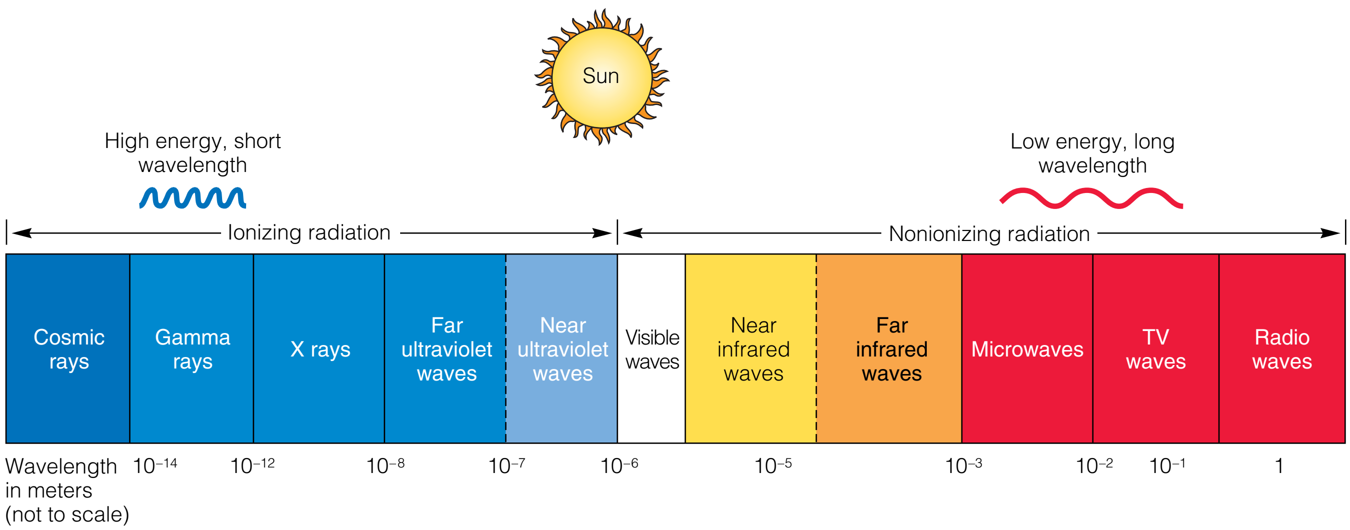


Figure 3-9 The *electromagnetic spectrum:* the range of electromagnetic waves, which differ in wavelength (distance between successive peaks or troughs) and energy content.

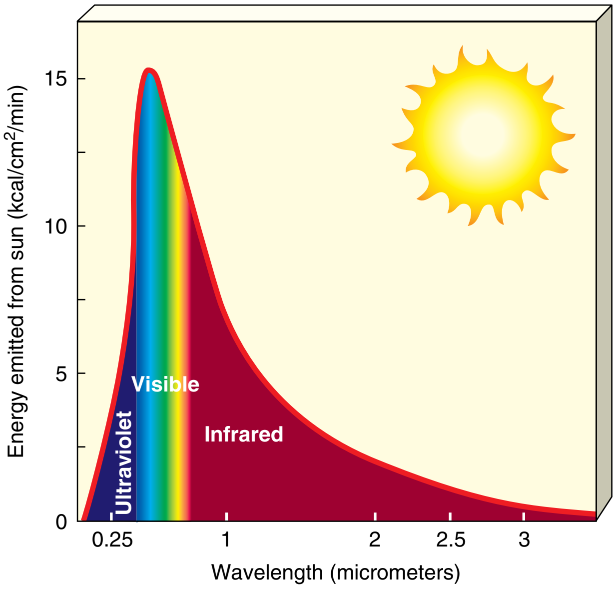


Figure 3-10 **Solar capital:** the spectrum of electromagnetic radiation released by the sun consists mostly of visible light.

Cosmic rays, gamma rays, X rays, and ultraviolet radiation (Figure 3-9, left side) are called **ionizing radiation** because they have enough energy to knock electrons from atoms and change them to positively charged ions. The resulting highly reactive electrons and ions can disrupt living cells, interfere with body processes, and cause many types of sickness, including various cancers. The other forms of electromagnetic radiation (Figure 3-9, right side) do not contain enough energy to form ions and are called **nonionizing radiation.** No scientific consensus exists on whether nonionizing forms of electromagnetic radiation given off when an electric current passes through a wire or a motor is harmful to humans.

The visible light that you can detect with your eyes is a form of nonionizing radiation that occupies only a small portion of the full range, or spectrum, of different types of electromagnetic radiation. We are energy challenged because our senses can detect only a tiny amount of the different types of electromagnetic radiation that are all around us. Figure 3-10 shows that visible light makes up most of the spectrum of electromagnetic radiation emitted by the sun.

What Is Heat and How Is It Transferred? Three Ways to Tango

Heat is the total kinetic energy of all the parts of a sample of matter and is transferred from one place to another by convection, conduction, and radiation.

Heat is the total kinetic energy of all the moving atoms, ions, or molecules within a given substance, excluding the overall motion of the whole object. For example, a glass of water consists of zillions of water molecules in constant motion. The heat stored in this sample of water is the total kinetic energy of all of these moving molecules. The term *heat* is also used to describe the energy that can be transferred between objects at different temperatures.

Temperature is the average speed of motion of the atoms, ions, or molecules in a sample of matter at a given moment. For example, the molecules in a sample of water in a glass have a certain average speed of motion. This is what we call its temperature.

Heat can be transferred from one place to another by three different methods. Study Figure 3-11 for an explanation of these methods.

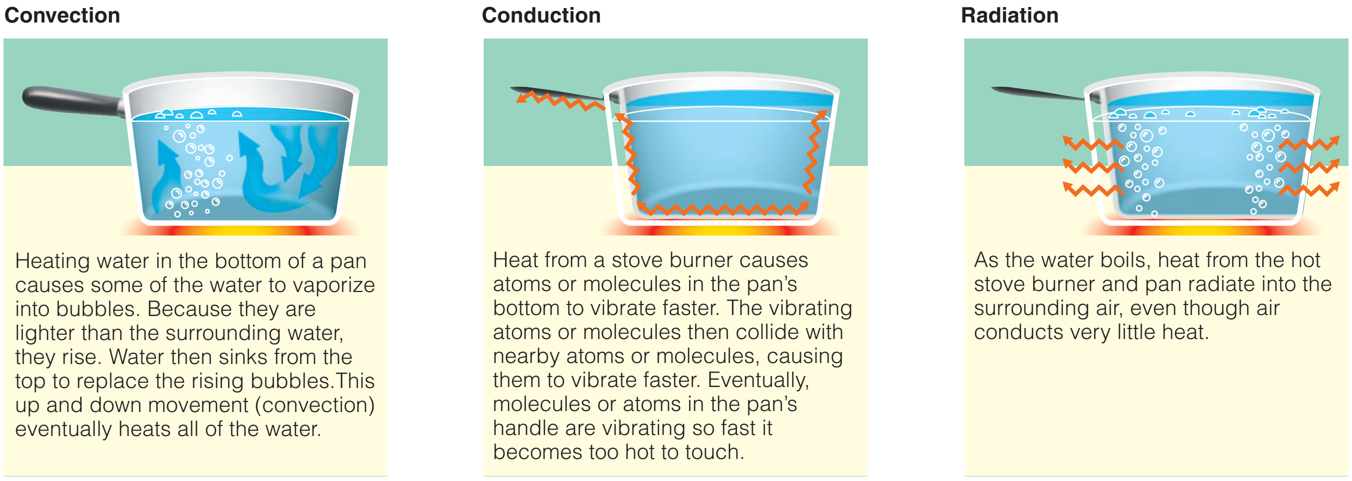


Figure 3-11 Three ways in which heat can be transferred from one place to another.

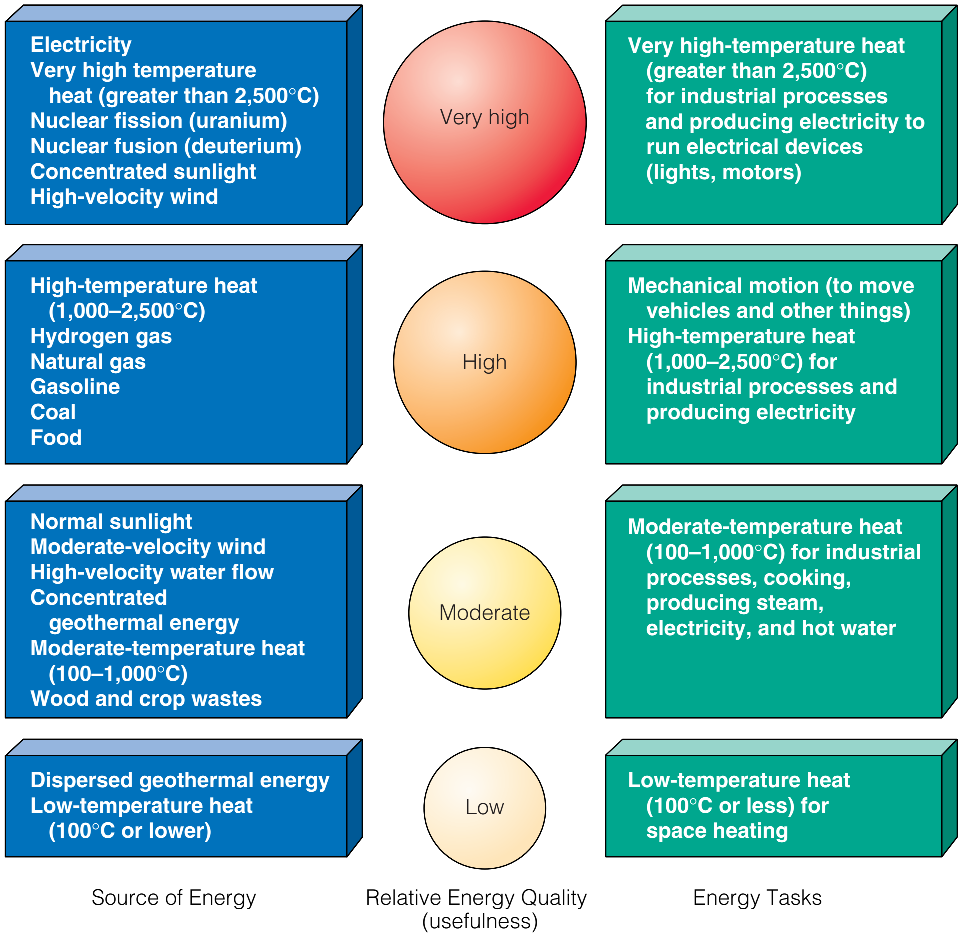


Figure 3-12 Categories of energy quality. *High-quality energy* is concentrated and has great ability to perform useful work. *Low-quality energy* is dispersed and has little ability to do useful work. To avoid unnecessary energy waste, it is best to match the quality of an energy source with the quality of energy needed to perform a task.

What Is Energy Quality? Energy Usefulness

Energy can be classified as having high or low quality depending on how useful it is to us as a resource.

Energy quality is a measure of an energy source's ability to do useful work, as seen in Figure 3-12. **High-quality energy** is concentrated and can perform much useful work. Examples are electricity, the chemical energy stored in coal and gasoline, concentrated sunlight, and nuclei of uranium-235 used as fuel in nuclear power plants.

By contrast, **low-quality energy** is dispersed and has little ability to do useful work. An example of low-quality energy is heat dispersed in the moving molecules of a large amount of matter (such as the atmosphere or a large body of water) so that its temperature is low.

For example, the total amount of heat stored in the Atlantic Ocean is greater than the amount of high-quality chemical energy stored in all the oil deposits of Saudi Arabia. Yet the ocean's heat is so widely dispersed, it cannot be used to move things or to heat things to high temperatures.

It makes sense to match the quality of an energy source with the quality of energy needed to perform a particular task (Figure 3-12) because doing so saves energy and usually money.

3-5 THE LAW OF CONSERVATION OF MATTER: A RULE WE CANNOT BREAK

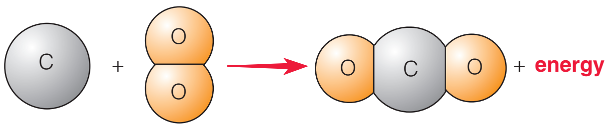
What Is the Difference between a Physical and a Chemical Change? Changes in Form and in Chemical Makeup

Matter can change from one physical form to another or change its chemical composition.

When a sample of matter undergoes a **physical change,** its chemical composition is not changed. A piece of aluminum foil cut into small pieces is still aluminum foil. When solid water (ice) is melted or liquid water is boiled, none of the H_2O molecules involved are altered; instead, the molecules are organized in different spatial (physical) patterns.

In a **chemical change,** or **chemical reaction,** there is a change in the chemical composition of the elements or compounds. Chemists use shorthand chemical equations to represent what happens in a chemical reaction. For example, when coal burns completely, the solid carbon (C) it contains combines with oxygen gas (O_2) from the atmosphere to form the gaseous compound carbon dioxide (CO_2):

Reactant(s)		→	**Product(s)**	
carbon	+ oxygen	→	carbon dioxide	+ **energy**
C	+ O_2	→	CO_2	+ **energy**



black solid *colorless gas* *colorless gas*

Energy is given off in this reaction, making coal a useful fuel. The reaction also shows how the complete burning of coal (or any of the carbon-containing compounds in wood, natural gas, oil, and gasoline) gives off carbon dioxide gas. This is a key gas that helps warm the lower atmosphere (troposphere).

The Law of Conservation of Matter: Why There Is No "Away"

When a physical or chemical change occurs, no atoms are created or destroyed.

We may change various elements and compounds from one physical or chemical form to another, but in no physical and chemical change can we create or destroy any of the atoms involved. All we can do is rearrange them into different spatial patterns (physical changes) or different combinations (chemical changes). This statement, based on many thousands of measurements, is known as the **law of conservation of matter.**

The law of conservation of matter means there is no "away" as in "to throw away." *Everything we think we have thrown away is still here somewhere on the planet with us in one form or another.* Dust and soot from the smokestacks of industrial plants, substances removed from polluted water at sewage treatment plants, and banned chemicals like DDT all have to go somewhere and can come back around to haunt us. For example, selling DDT abroad means it can return to the United States as residues in imported coffee, fruit, and other foods, or as fallout from air masses moved long distances by winds.

How Do Chemists Keep Track of Atoms? Atomic Bookkeeping

Chemical equations are used as an accounting system to verify that no atoms are created or destroyed in a chemical reaction.

In keeping with the law of conservation of matter, each side of a chemical equation must have the same number of atoms of each element involved. Minding this law leads to what chemists call a *balanced chemical equation.*

The equation for the burning of carbon ($C + O_2 \rightarrow CO_2$) is balanced because one atom of carbon and two atoms of oxygen are on both sides of the equation. That is an easy one.

Now we try a slightly harder one. When electricity is passed through water (H_2O), the water molecule can be broken down into hydrogen (H_2) and oxygen (O_2). This chemical reaction can be represented by the following shorthand chemical equation:

H_2O	→	H_2	+	O_2
2 H atoms 1 O atom		2 H atoms		2 O atoms

This equation is unbalanced because one atom of oxygen is on the left but two atoms are on the right.

We cannot change the subscripts of any of the formulas to balance this equation because that would make the substances different from those actually involved. That is a no-no according to the law of conservation of matter. Instead, we could use different numbers of the *molecules* involved to balance the equation. For example, we could use two water molecules:

$2\ H_2O$	→	H_2	+	O_2
4 H atoms 2 O atoms		2 H atoms		2 O atoms

This equation is still unbalanced because although the numbers of oxygen atoms on both sides are now equal, the numbers of hydrogen atoms are not.

We can correct this by having the reaction produce two hydrogen molecules:

$2\ H_2O$	→	$2\ H_2$	+	O_2
4 H atoms 2 O atoms		4 H atoms		2 O atoms

Now the equation is balanced, and the law of conservation of matter has been observed. We see that for every two molecules of water through which we pass electricity, two hydrogen molecules and one oxygen molecule are produced. By the way, this equation may change your life. It represents how we could use heat or electricity to decompose water and produce hydrogen gas that someday may replace oil as a fuel to power our societies—more on this hydrogen revolution in Chapter 18.

Ready for a little more practice? Try to balance the chemical equation for the reaction of nitrogen gas (N_2) with hydrogen gas (H_2) to form ammonia gas (NH_3).

How Harmful Are Pollutants? Too Much of Bad Things

The law of conservation of matter tells us that we will always produce some pollutants, but we can produce much less and clean up some of what we do produce.

We can make the environment cleaner and convert some potentially harmful chemicals into less harmful physical or chemical forms. But *the law of conservation of matter means we will always face the problem of what to do with some quantity of wastes and pollutants.*

Three factors determining the severity of a pollutant's harmful effects are its *chemical nature,* its *concentration,* and its *persistence.*

The second of these factors, *concentration,* is sometimes expressed in *parts per million (ppm);* 1 ppm corresponds to 1 part pollutant per million parts of the gas, liquid, or solid mixture in which the pollutant is found. Smaller concentration units are parts per billion (ppb) and parts per trillion (ppt).

We can reduce the concentration of a pollutant by dumping it into the air or a large volume of water, but there are limits to the effectiveness of this dilution approach. For example, the water flowing in a river can dilute or disperse some of the wastes we dump into the river. But if we dump in too much waste this natural cleansing process does not work.

The third factor, **persistence,** is a measure of how long the pollutant stays in the air, water, soil, or body. Pollutants can be classified into four categories based on their persistence. **Degradable,** or **nonpersistent, pollutants** are broken down completely or reduced to acceptable levels by natural physical, chemical, and biological processes. Complex chemical pollutants that living organisms (usually specialized bacteria) break down into simpler chemicals are called **biodegradable pollutants.** Human sewage in a river, for example, is biodegraded fairly quickly by bacteria if the sewage is not added faster than it can be broken down.

Slowly degradable, or **persistent, pollutants** take decades or longer to degrade. Examples include the insecticide DDT and most plastics.

Nondegradable pollutants are chemicals that natural processes cannot break down. Examples include the toxic elements lead, mercury, and arsenic. Ideally, we should try not to use these chemicals, but if we do, we should figure out ways to keep them from getting into the environment.

3-6 NUCLEAR CHANGES

What Is Natural Radioactivity? Nuclei Losing Particles or Radiation

An atom can change from one isotope to another when its nucleus loses particles or gives off high-energy electromagnetic radiation.

In addition to physical and chemical changes, matter can undergo a third type of change known as a **nuclear change.** This occurs when nuclei of certain isotopes spontaneously change or are made to change into nuclei of different isotopes.

Three types of nuclear change are natural radioactive decay, nuclear fission, and nuclear fusion. **Natural radioactive decay** is a nuclear change in which unstable isotopes spontaneously emit fast-moving chunks of matter (called particles), high-energy radiation, or both at a fixed rate. The unstable isotopes are called **radioactive isotopes** or **radioisotopes.** Radioactive decay of these isotopes into various other isotopes continues until the original isotope is changed into a stable isotope that is not radioactive.

Radiation emitted by radioisotopes is damaging ionizing radiation. The most common form of ionizing energy released from radioisotopes is **gamma rays,** a form of high-energy electromagnetic radiation. You do not want to get exposed to these waves.

High-speed ionizing particles emitted from the nuclei of radioactive isotopes are most commonly of two types: **alpha particles** (fast-moving, positively charged chunks of matter that consist of two protons and two neutrons) and **beta particles** (high-speed electrons).

Each type of radioisotope spontaneously decays at a characteristic rate into a different isotope. This rate of decay can be expressed in terms of **half-life:** the time needed for *one-half* of the nuclei in a given quantity of a radioisotope to decay and emit their radiation to form a different isotope (Figure 3-13). The decay continues, often producing a series of different radioisotopes, until a nonradioactive isotope is formed.

Each radioisotope has a characteristic half-life, which may range from a few millionths of a second to several billion years (Table 3-1, right). An isotope's half-life cannot be changed by temperature, pressure, chemical reactions, or any other known factor.

Half-life can be used to estimate how long a sample of a radioisotope must be stored in a safe container before it decays to what is considered a safe level. A general rule is that such decay takes about 10 half-lives. Thus people must be protected from radioactive waste containing iodine-131 (which concentrates in the thyroid gland and has a half-life of 8 days) for 80 days (10×8 days). Plutonium-239, which is produced in nuclear reactors and used as the explosive in some

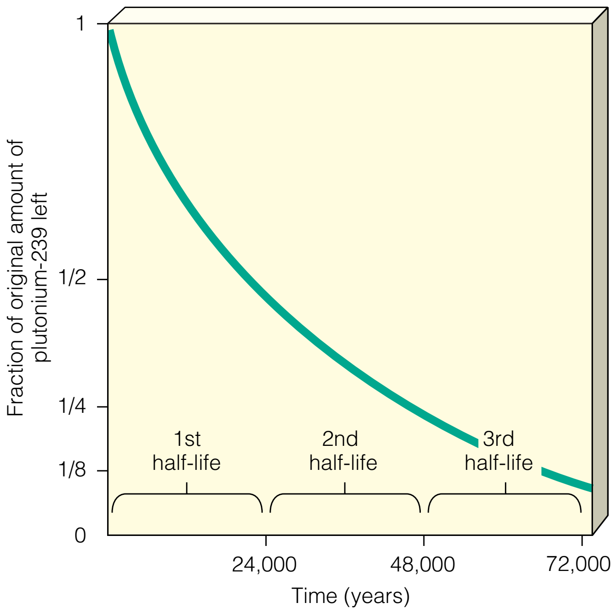


Figure 3-13 *Half-life.* The radioactive decay of plutonium-239, which is produced in nuclear reactors and used as the explosive in some nuclear weapons, has a half-life of 24,000 years. The amount of radioactivity emitted by a radioactive isotope decreases by one-half for each half-life that passes. Thus, after three half-lives, amounting to 72,000 years, one-eighth of a sample of plutonium-239 would still be radioactive.

nuclear weapons, can cause lung cancer when its particles are inhaled in minute amounts. Its half-life is 24,000 years. Thus it must be stored safely for 240,000 years ($10 \times 24{,}000$ years)—about four times longer than the latest version of our species (*Homo sapiens*) has existed. Chapter 17 has more on the problem of what to do with the nuclear wastes we have created.

Table 3-1 Half-Lives of Selected Radioisotopes

Isotope	Half-Life	Radiation Emitted
Potassium-42	12.4 hours	Alpha, beta
Iodine-131	8 days	Beta, gamma
Cobalt-60	5.27 years	Beta, gamma
Hydrogen-3 (tritium)	12.5 years	Beta
Strontium-90	28 years	Beta
Carbon-14	5,370 years	Beta
Plutonium-239	24,000 years	Alpha, gamma
Uranium-235	710 million years	Alpha, gamma
Uranium-238	4.5 billion years	Alpha, gamma

Exposure to ionizing radiation from alpha particles, beta particles, and gamma rays can damage cells in two ways. One is *genetic damage* from mutations or changes in DNA molecules that alter genes and chromosomes. If the mutation is harmful, it can lead to genetic defects in the next generation of offspring or several generations later.

The other is *somatic damage* to tissues, which causes harm during the victim's lifetime. Examples include burns, miscarriages, eye cataracts, and certain cancers.

According to the U.S. National Academy of Sciences, exposure over an average lifetime to average levels of ionizing radiation from natural and human sources causes about 1% of all fatal cancers and 5–6% of all normally encountered genetic defects in the U.S. population.

What Is Nuclear Fission? Splitting Heavy Nuclei

Neutrons can split apart the nuclei of certain isotopes with large mass numbers and release a large amount of energy.

Nuclear fission is a nuclear change in which nuclei of certain isotopes with large mass numbers (such as uranium-235) are split apart into lighter nuclei when struck by neutrons; each fission releases two or three more neutrons and energy (Figure 3-14, p. 50). Each of these neutrons, in turn, can cause an additional fission. For these multiple fissions to take place, enough fissionable nuclei must be present to provide the **critical mass** needed for efficient capture of these neutrons.

Multiple fissions within a critical mass form a **chain reaction,** which releases an enormous amount of energy (Figure 3-15, p. 50). This is somewhat like a room in which the floor is covered with spring-loaded mousetraps, each topped by a Ping-Pong ball. Open the door, throw in a single Ping-Pong ball, and watch the action in this simulated chain reaction of snapping mousetraps and balls flying around in every direction.

In an atomic bomb, an enormous amount of energy is released in a fraction of a second in an uncontrolled nuclear fission chain reaction. This reaction is initiated by an explosive charge, which pushes two masses of fissionable fuel together. This causes the fuel to reach the critical mass needed for a chain reaction and to give off a tremendous amount of energy in a gigantic explosion.

In the reactor of a nuclear power plant, the rate at which the nuclear fission chain reaction takes place is

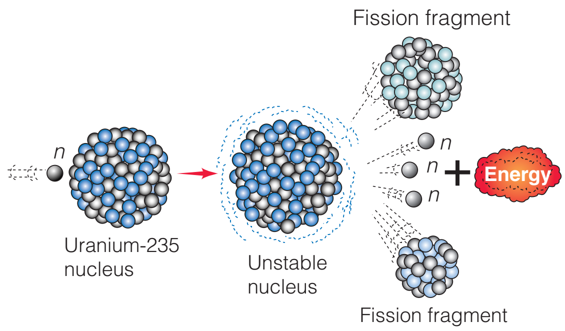


Figure 3-14 Fission of a uranium-235 nucleus by a neutron (*n*).

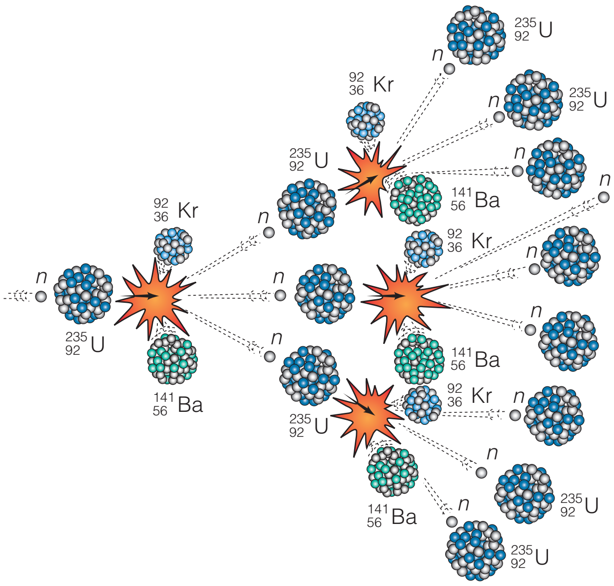


Figure 3-15 A *nuclear chain reaction* initiated by one neutron triggering fission in a single uranium-235 nucleus. This figure illustrates only a few of the trillions of fissions caused when a single uranium-235 nucleus is split within a critical mass of uranium-235 nuclei. The elements krypton (Kr) and barium (Ba), shown here as fission fragments, are only two of many possibilities.

controlled so that under normal operation only one of every two or three neutrons released is used to split another nucleus. In conventional nuclear fission reactors, the splitting of uranium-235 nuclei releases heat, which produces high-pressure steam to spin turbines and thus generate electricity.

What Is Nuclear Fusion? Forcing Light Nuclei to Combine

Extremely high temperatures can force the nuclei of isotopes of some lightweight atoms to fuse together and release large amounts of energy.

Nuclear fusion is a nuclear change in which two isotopes of light elements, such as hydrogen, are forced together at extremely high temperatures until they fuse to form a heavier nucleus. Lots of energy is released when this happens. Temperatures of at least 100 million °C are needed to force the positively charged nuclei (which strongly repel one another) to fuse.

Nuclear fusion is much more difficult to initiate than nuclear fission, but once started it releases far more energy per unit of fuel than does fission. You would not be alive without nuclear fusion. Fusion of hydrogen nuclei to form helium nuclei is the source of energy in the sun and other stars.

After World War II, the principle of *uncontrolled nuclear fusion* was used to develop extremely powerful hydrogen, or thermonuclear, weapons. These weapons use the D–T fusion reaction, in which a hydrogen-2, or deuterium (D), nucleus and a hydrogen-3 (tritium, T) nucleus are fused to form a larger, helium-4 nucleus, a neutron, and energy, as shown in Figure 3-16.

Scientists have also tried to develop *controlled nuclear fusion,* in which the D–T reaction is used to pro-

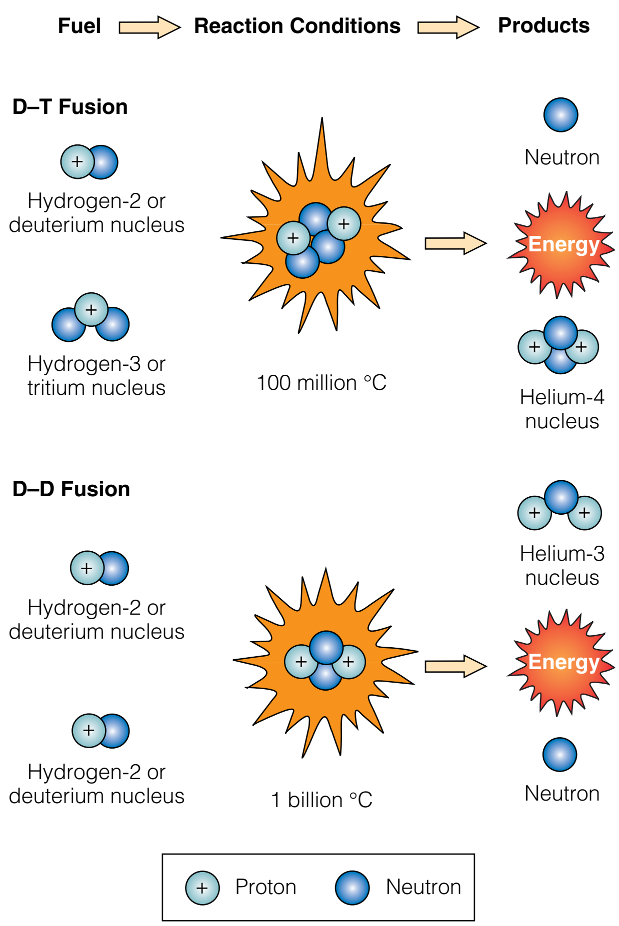


Figure 3-16 The deuterium–tritium (D–T) and deuterium–deuterium (D–D) *nuclear fusion* reactions, which take place at extremely high temperatures.

duce heat that can be converted into electricity. After more than 50 years of research, this process is still in the laboratory stage. Even if it becomes technologically and economically feasible, many energy experts do not expect it to be a practical source of energy until 2030, if then.

3-7 ENERGY LAWS: TWO RULES WE CANNOT BREAK

What Is the First Law of Thermodynamics? You Cannot Get Something for Nothing

In a physical or chemical change, we can change energy from one form to another but we can never create or destroy any of the energy involved.

Scientists have observed energy being changed from one form to another in millions of physical and chemical changes. But they have never been able to detect the creation or destruction of any energy (except in nuclear changes). The results of their experiments have been summarized in the **law of conservation of energy,** also known as the **first law of thermodynamics:** *In all physical and chemical changes, energy is neither created nor destroyed, but it may be converted from one form to another.*

This scientific law tells us that when one form of energy is converted to another form in any physical or chemical change, *energy input always equals energy output.* No matter how hard we try or how clever we are, we cannot get more energy out of a system than we put in; in other words, *we cannot get something for nothing in terms of energy quantity.* This is one of Mother Nature's basic rules that we have to live with.

What Is the Second Law of Thermodynamics? You Cannot Even Break Even

Whenever energy is changed from one form to another we always end up with less usable energy than we started with.

Because the first law of thermodynamics states that energy can be neither created nor destroyed, we may be tempted to think we will always have enough energy. Yet if we fill a car's tank with gasoline and drive around or use a flashlight battery until it is dead, something has been lost. If it is not energy, what is it? The answer is *energy quality* (Figure 3-12), the amount of energy available that can perform useful work.

Countless experiments have shown that when energy is changed from one form to another, a decrease in energy quality always occurs. The results of these experiments have been summarized in what is called the **second law of thermodynamics:** *When energy is changed from one form to another, some of the useful energy is always degraded to lower quality, more dispersed, less useful energy.* This degraded energy usually takes the form of heat given off at a low temperature to the surroundings (environment). There it is dispersed by the random motion of air or water molecules and becomes even less useful as a resource.

In other words, *we cannot even break even in terms of energy quality because energy always goes from a more useful to a less useful form when energy is changed from one form to another.* No one has ever found a violation of this fundamental scientific law. It is another one of Mother Nature's basic rules that we have to live with.

Consider three examples of the second law of thermodynamics in action. *First,* when a car is driven, only about 20–25% of the high-quality chemical energy available in its gasoline fuel is converted into mechanical energy (to propel the vehicle) and electrical energy (to run its electrical systems). The remaining 75–80% is degraded to low-quality heat that is released into the environment and eventually lost into space. Thus, most of the money you spend for gasoline is not used to get you anywhere.

Second, when electrical energy flows through filament wires in an incandescent lightbulb, it is changed into about 5% useful light and 95% low-quality heat that flows into the environment. In other words, this so-called *light bulb* is really a *heat bulb. Good news.* Scientists have developed compact fluorescent bulbs that are four times more efficient, and even more efficient bulbs are on the way. Do you use compact fluorescent bulbs?

Third, in living systems, solar energy is converted into chemical energy (food molecules) and then into mechanical energy (moving, thinking, and living). During each of these conversions, high-quality energy is degraded and flows into the environment as low-quality heat (Figure 3-17, p. 52). Trace the flows and energy conversions in this diagram.

The second law of thermodynamics also means that *we can never recycle or reuse high-quality energy to perform useful work.* Once the concentrated energy in a serving of food, a liter of gasoline, a lump of coal, or a chunk of uranium is released, it is degraded to low-quality heat that is dispersed into the environment.

Energy efficiency, or **energy productivity,** is a measure of how much useful work is accomplished by a particular input of energy into a system. *Good news.* There is plenty of room for improving energy efficiency. Scientists estimate that only about 16% of the energy used in the United States ends up performing useful work. The remaining 84% is either unavoidably wasted because of the second law of thermodynamics (41%) or unnecessarily wasted (43%).

Here is a lesson from thermodynamics. The cheapest and quickest way for us to get more energy is to

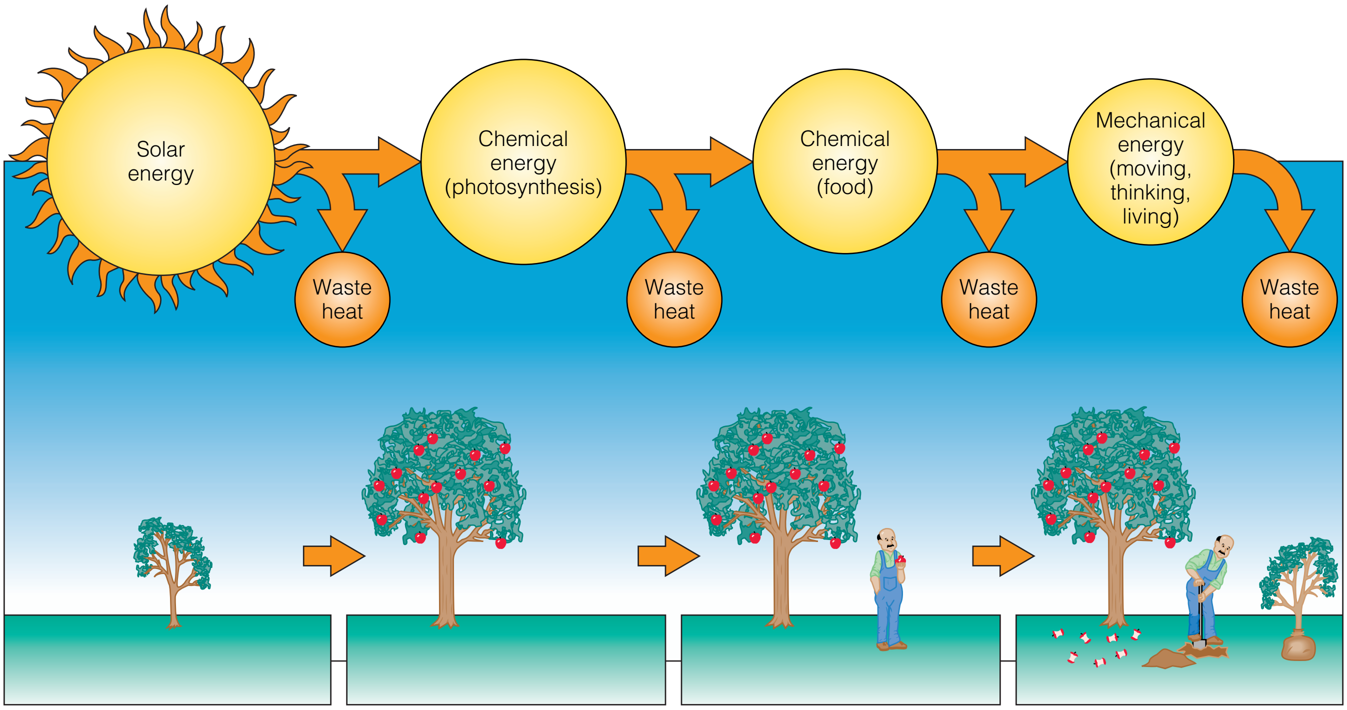


Figure 3-17 The second law of thermodynamics in action in living systems. Each time energy is changed from one form to another, some of the initial input of high-quality energy is degraded, usually to low-quality heat that is dispersed into the environment.

stop unnecessarily wasting almost half of the energy we use. We can do this by not driving gas-guzzling motor vehicles and by not living in poorly insulated and leaky houses. What are you doing to reduce your unnecessary waste of energy?

3-8 MATTER AND ENERGY LAWS AND ENVIRONMENTAL PROBLEMS

What Is a High-Throughput Economy? An Accelerating Treadmill

Most of today's economies increase economic growth by converting the world's resources to goods and services in ways that add large amounts of waste, pollution, and low-quality heat to the environment.

As a result of the law of conservation of matter and the second law of thermodynamics, individual resource use automatically adds some waste heat and waste matter to the environment. Most of today's advanced industrialized countries have **high-throughput (high-waste) economies** that attempt to sustain ever-increasing economic growth by increasing the one-way flow of matter and energy resources through their economic systems (Figure 3-18). These resources flow through their economies into planetary *sinks* (air, water, soil, organisms), where pollutants and wastes end up and can accumulate to harmful levels.

What happens if more and more people continue to use and waste more and more energy and matter resources at an increasing rate? In other words, what happens if most of the world's people get infected with the affluenza virus?

The law of conservation of matter and the two laws of thermodynamics discussed in this chapter tell us that eventually this consumption will exceed the capacity of the environment to dilute and degrade waste matter and absorb waste heat. However, they do not tell us how close we are to reaching such limits.

What Is a Matter-Recycling-and-Reuse Economy? Go in Circles Instead of Straight Lines

Recycling and reusing more of the earth's matter resources slows down depletion of nonrenewable matter resources and reduces our environmental impact.

There is a way to slow down the resource use and reduce our environmental impact in a high-throughput economy. We can convert such a linear high-throughput economy into a circular **matter-recycling-and-reuse economy** that recycles and reuses our matter outputs back instead of dumping them into the environment.

Changing to a matter-recycling-and-reuse economy is an important way to buy some time. But this does not allow more and more people to use more and more resources indefinitely, even if all of them were

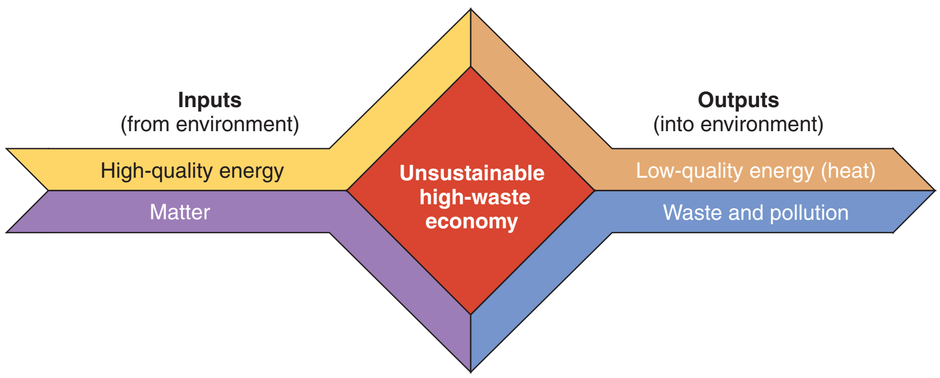


Figure 3-18 The *high-throughput economies* of most developed countries are based on continually increasing the rates of energy and matter flow. This produces valuable goods and services but also converts high-quality matter and energy resources into waste, pollution, and low-quality heat.

somehow perfectly recycled and reused. The reason is that the two laws of thermodynamics tell us that recycling and reusing matter resources always requires using high-quality energy (which cannot be recycled) and adds waste heat to the environment.

What Is a Low-Throughput Economy? Learning from Nature

We can live more sustainably by reducing the throughput of matter and energy in our economies, not wasting matter and energy resources, recycling and reusing most of the matter resources we use, and stabilizing the size of our population.

Is there a better way out of the environmental situation that we have gotten ourselves into? You bet. The three scientific laws governing matter and energy changes suggest that the best long-term solution to our environmental and resource problems is to shift from an economy based on increasing matter and energy flow (throughput) to a more sustainable **low-throughput (low-waste) economy,** as summarized in Figure 3-19. This means building on the concept of recycling and reusing as much matter as possible by also reducing the throughput of matter and energy through an economy. This can be done by wasting less matter and energy, living more simply to decrease resource use per person, and slowing population growth to reduce the

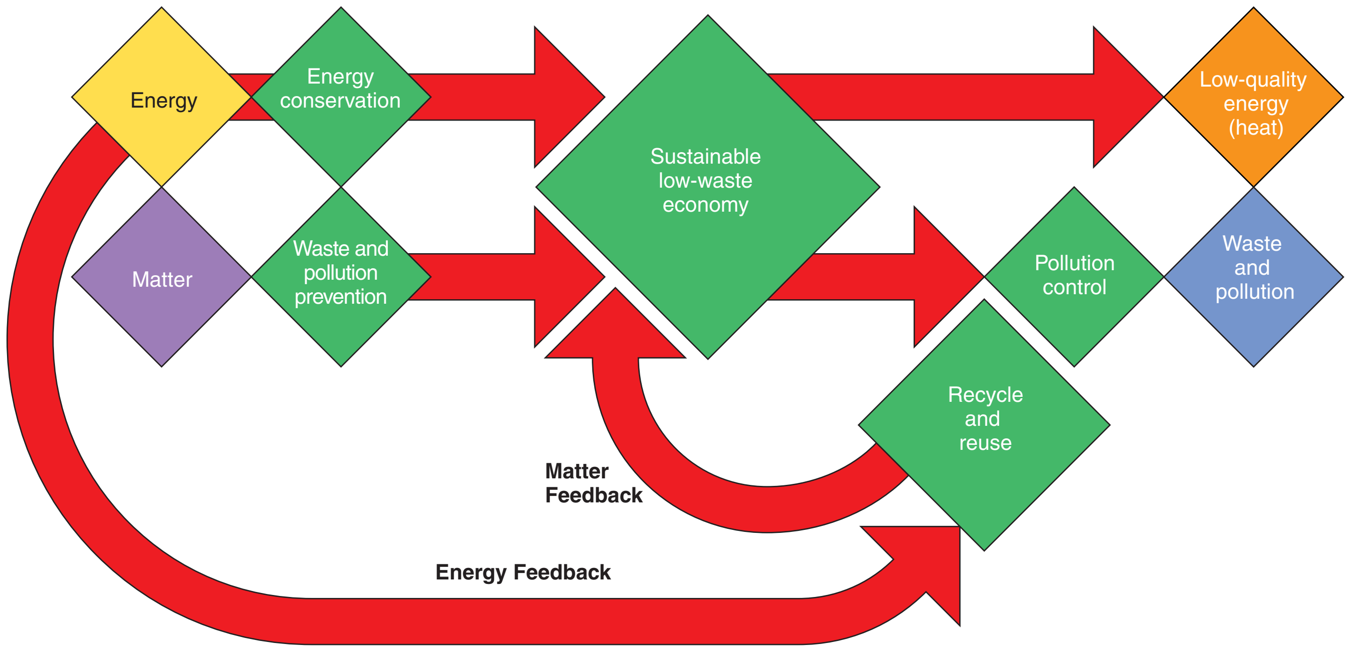


Figure 3-19 **Solutions:** lessons from nature. A *low-throughput economy,* based on energy flow and matter recycling, works with nature to reduce the throughput of matter and energy resources (items shown in green). This is done by (1) reusing and recycling most nonrenewable matter resources, (2) using renewable resources no faster than they are replenished, (3) using matter and energy resources efficiently, (4) reducing unnecessary consumption, (5) emphasizing pollution prevention and waste reduction, and (6) controlling population growth.

number of resource users. In other words, we learn to live more sustainably by heeding the *lessons from nature* revealed by the law of conservation of mass and the two laws of thermodynamics.

The next five chapters apply the three basic scientific laws of matter and thermodynamics to living systems and look at some *biological principles* that can also teach us how to live more sustainably by working with nature.

The second law of thermodynamics holds, I think, the supreme position among laws of nature. . . . If your theory is found to be against the second law of thermodynamics, I can give you no hope.

ARTHUR S. EDDINGTON

CRITICAL THINKING

1. Respond to the following statements:

a. Scientists have not absolutely proven that anyone has ever died from smoking cigarettes.

b. The greenhouse theory—that certain gases (such as water vapor and carbon dioxide) warm the atmosphere—is not a reliable idea because it is only a scientific theory.

2. See whether you can find an advertisement or an article describing some aspect of science in which **(a)** the concept of scientific proof is misused, **(b)** the term *theory* is used when it should have been *hypothesis,* and **(c)** a consensus scientific finding is dismissed or downplayed because it is "only a theory" or is not viewed as sound science.

3. How does a scientific law (such as the law of conservation of matter) differ from a societal law (such as maximum speed limits for vehicles)? Can each be broken? Explain.

4. A tree grows and increases its mass. Explain why this is not a violation of the law of conservation of matter

5. If there is no "away," why is the world not filled with waste matter?

6. Methane (CH_4) gas is the major component of natural gas. Write and balance the chemical equation for the burning of methane when it combines with oxygen gas in the atmosphere to form carbon dioxide and water.

7. Suppose you have 100 grams of radioactive plutonium-239 with a half-life of 24,000 years. How many grams of plutonium-239 will remain after **(a)** 12,000 years, **(b)** 24,000 years, and **(c)** 96,000 years?

8. Someone wants you to invest money in an automobile engine that will produce more energy than the energy in the fuel (such as gasoline or electricity) you use to run the motor. What is your response? Explain.

9. Use the second law of thermodynamics to explain why a barrel of oil can be used only once as a fuel.

PROJECTS

1. Use the library or Internet to find an example of junk science and explain why it is junk science. Compare your findings with those of your classmates.

2. **(a)** List two examples of negative feedback loops not discussed in this chapter, one that is beneficial and one that is detrimental. Compare your examples with those of your classmates. **(b)** Give two examples of positive feedback loops not discussed in this chapter. Include one that is beneficial and one that is detrimental. Compare your examples with those of your classmates.

3. If you have the use of a sensitive balance, try to demonstrate the law of conservation of mass in a physical change. Weigh a container with a lid (a glass jar will do), add an ice cube and weigh it again, and then allow the ice to melt and weigh it again. Explain how your results obey the law of conservation of matter.

4. Use the library or Internet to find examples of various perpetual motion machines and inventions that allegedly violate the two laws of thermodynamics by producing more high-quality energy than the high-quality energy needed to make them run. What has happened to these schemes and machines—many of them developed by scam artists to attract money from investors?

5. Use the library or the Internet to find bibliographic information about *Warren Weaver* and *Arthur S. Eddington,* whose quotes appear at the beginning and end of this chapter.

6. Make a concept map of this chapter's major ideas using the section heads, subheads, and key terms (in boldface). Look on the website for this book for information about making concept maps.

LEARNING ONLINE

The website for this book contains study aids and many ideas for further reading and research. They include a chapter summary, review questions for the entire chapter, flash cards for key terms and concepts, a multiple-choice practice quiz, interesting Internet sites, references, and a guide for accessing thousands of InfoTrac® College Edition articles. Log on to

http://biology.brookscole.com/miller14

Then click on the Chapter-by-Chapter area, choose Chapter 3, and select a learning resource.