Matter, Energy, and Life An introduction to chemical concepts

fourth edition

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Preface to the Fourth Edition

The widespread acceptance of *Matter, Energy, and Life* since its first appearance 15 years ago has been most gratifying, and it is with pleasure we present our users, both new and old, with this fourth edition. As with previous editions, we have relied heavily upon user feedback, both instructor and student, to improve clarity and increase comprehension, as well as concentrating on keeping the content up-to-date and consonant with significant new developments in the fields of inorganic and organic chemistry and biochemistry. The increasing use of *Matter, Energy, and Life* in programs for health care professionals has led us to incorporate supplements designed to show students how the theoretical material they are learning relates directly or indirectly to laboratory or clinical analyses and techniques. For outstanding assistance with these we are indebted to Dr. Alice Holtz of Boston University.

The reader who is familiar with the earlier editions of *Matter, Energy, and Life* will find that the goals and organization of the book remain the same. The level of presentation has not changed, and the chapters remain as independent of each other as possible to permit selective, nonsequential use. The book remains introductory and requires no prior knowledge of atomic or molecular structure or the principles of chemical bonding.

The authors wish to thank James H. Funston, formerly Instructor of Biology at Holy Cross, Worcester, Massachusetts, for applying his expertise in both biochemistry and editorial revision. His considerable effort has helped to make the present edition a significant step toward our goal of maximum accuracy and readability.

Middletown, Connecticut J.J.W.B.
St. Louis, Missouri G.E.A.
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Chapter 1

Matter and Energy

The first atomic bomb exploded on a New Mexico desert in 1945. The sound foretold the end of World War II and the beginning of a new scientific era. Within the bomb, a small amount of matter became a large amount of energy. Long thought by the public to be separate and distinct, matter and energy were dramatically shown to be closely interrelated. This point would be expanded, were this book for physics or chemistry students. But it is not. It is for biology students.

In the chemistry of life, very little matter is converted into energy. So little, in fact, it can be ignored. Therefore, biologists still like to make a general distinction between them. This book will deal with matter and energy as though they were both clearly defined and separate concepts. In reality, they are neither.

What are matter and energy? What role do they play in the physics and chemistry of living organisms? Neither of these questions has yet been completely answered. Nor will they be in this book. Yet both matter and energy play such an important part in the living world that some knowledge of their characteristics is essential to the study of biology. The reason is quite simple. All living things are composed of matter. The expression of the release and use of energy by living matter is the thing we call "life." When this release and use of energy ceases, we call it death.

1–1 MATTER: CONCEPTS OF MASS, WEIGHT, AND DENSITY

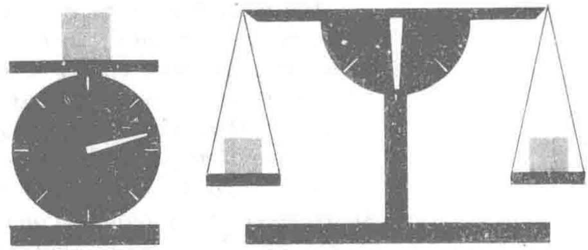
Matter can be defined as that which has *mass* and occupies space. Stones, water, gases, animals, or plants: all are composed of matter. Since the scientific conceptions of mass and weight are important to an understanding of matter, it is well to examine them at the outset.

When an object is placed on a scale, it registers a certain *weight*. This means that the force of gravity pulls this object toward the earth to a degree measured by the lowering of the scale's platform. The greater the attraction between the earth and the object, the greater the weight of the object. Weight can be measured in such units as ounces, pounds, or tons. So long as the same scale of measurement is used, the relative weights of objects may be easily established and compared.

However, the use of weight as a concept predates its use in science. Therefore it has very serious limitations for modern research. A man in space may encounter a situation where neither he nor the objects around him seem to have any weight. Objects within the spacecraft not fastened down float about freely in their condition of so-called "weightlessness."

The reason is simple. Weight varies according to the force of gravitational attraction. Gravitational attraction, in turn, is dependent upon several factors. One of these is the distance from the center of the earth. A man who weighs 144 pounds on the earth's surface would weigh only 36 pounds when he was 8000 miles high, 16 pounds at 12,000 miles, and 9 pounds at 16,000 miles. Gravity, and therefore weight, is dependent on another factor. A 100-pound man would weigh only 20 pounds on the moon and about 37 pounds on Mars. Here the influencing factor is the quantity of matter in the body responsible for the pull of gravity. *The weight which a given bit of matter possesses is directly related to the force of gravity at the place where the measurement is made.*

The scientist, on the other hand, wants to describe matter in terms which are independent of the object's location. Certainly objects in a spaceship do not change their physical and chemical characteristics in the weightless condition. They still exist, occupy the same amount of space, and look the same as they do on earth. The weight of the objects has changed, but the quantity of matter present is still the same. The measure of this quantity of matter in the objects is called its *mass*. The *gram* is the fundamental unit of mass.



1–1
The scale on the left can determine weight but not mass. High above the earth, a reading would be less than it would deep in a valley. The balance scale on the right can determine both mass and weight. Since the force of gravity is the same on both pans, its effect is cancelled. Mass can therefore be determined by comparison with objects whose masses are known.

The mass of an object is not necessarily related to its size. A lead ball one foot in diameter will, of course, have less mass than a lead ball two feet in diameter. However, a lead ball one foot in diameter has a good deal more mass than an aluminum ball of the same dimensions. It is apparent, then, that there is another factor influencing mass. This factor is the *density* of matter. Density is a measure of the amount of matter in a given volume of space. Thus, the greater the amount of mass in a certain space, the greater the density. Cities, for example, are more densely populated than rural areas. This means that in equal areas of land, there are more people in the city than in the country.

Consider two solid aluminum spheres. The first is one foot in diameter, the second ten feet in diameter. Obviously, the mass of the ten-foot sphere is greater. The density, however, is the same for both.

1–2 ENERGY

In contrast to matter, energy neither occupies space nor has weight. There is no such thing, for example, as "3 cubic feet" or "4 pounds 3 ounces" of energy. How, then, can an amount of energy be measured?

Energy can only be measured by its effects upon matter. In general, the greater the effect, the greater the amount of energy. For example, under similar conditions, a stick of dynamite causes more damage to a house (matter) than a firecracker does. The dynamite releases more energy. The distance a ball (matter) travels after being batted is often, though not always, related to the amount of energy exerted by the batter.

The more matter there is to be moved, the more energy must be supplied to move it. In moving equal distances, a large animal generally uses more energy than a small one. This is one reason why large animals are usually less active than small ones. It also helps to explain why an overweight man places greater strain on his heart than a man of normal weight.

It is often useful to speak of energy as existing in one of two kinds, *kinetic* or *potential*. *Potential energy is energy that is stored, or inactive.* A stick of dynamite represents a great deal of potential energy. When released, potential energy is capable of causing an effect on matter. However, when it does so it is no longer potential energy. It is kinetic energy.

Kinetic energy is energy of motion. It is in the process of causing an effect on matter. Kinetic energy can be measured by determining how much matter it moves in a given period of time, and how far and how fast it moves it. Imagine a boulder perched on top of a hill, ready to roll down if given a slight push. In this state, the boulder and the hill are a physical system in which there is a certain amount of potential energy. As the boulder rolls down the hill, the potential energy in the system becomes kinetic. Matter is being moved. When the boulder reaches the bottom, it has converted all of its potential energy into kinetic energy. If the original system is to be re-established, the boulder must be moved back to the top of the hill. This requires an expenditure of energy. The energy necessary to get the boulder up the hill again is the same as the potential energy present in the system at the start. The conversion of potential energy to kinetic energy (the boulder going down the hill) and the conversion of kinetic energy to potential (moving the boulder back up the hill) has thus taken place.

Energy is constantly being changed from kinetic to potential and back again. The biological world is no exception. Living organisms operate by changing the potential energy found in foodstuffs into the kinetic energy of muscle contraction, manufacture of needed structural parts, etc. Energy is independent of life. *Life, however, is completely dependent upon energy.*

1–3 THE FORMS OF ENERGY

In addition to the two kinds of energy (potential and kinetic), five forms are recognized. These are *chemical, electrical, mechanical, radiant,* and *atomic energy*. The last of these, atomic energy, has little direct relationship to the normal functioning of living organisms. For this reason, atomic energy will not be included in this discussion. All forms of energy exist as either kinetic or potential energy.

Chemical energy. Chemical energy is the energy possessed by chemical compounds. Gasoline, for example, is basically a mixture of compounds that possess a certain amount of potential chemical energy. When gasoline is burned, its potential chemical energy is converted into kinetic energy. In the automobile engine, this kinetic energy moves the pistons up and down.

By releasing its chemical energy, gasoline is changed into two less complex substances, oxidized carbon and water. Like the boulder at the top of the hill, the gasoline contained a certain amount of potential energy. After the burning reaction, the end products resemble the boulder at the bottom of the hill. In each case, potential energy has been converted into kinetic.

Chemical energy can also be described in terms of building up chemical compounds from simpler parts. For example sunlight (radiant energy) is used in the leaves of green plants to build sugar and other compounds from carbon dioxide and water. This involves many chemical reactions. The end result is potential chemical energy stored in the sugar molecules. In this case, chemical energy is being *stored* by chemical reactions. This is analogous to carrying the boulder to the top of the hill.

Chemical compounds vary widely in both the amount of potential chemical energy they contain, and the ease with which this energy can be released. Gasoline, sugars, and fats contain a great deal of energy that is easily released. Other compounds such as water or carbon dioxide also contain potential chemical energy. However, a great deal of energy must be *expended* before the energy contained in these compounds is released.

Chemical energy is the most fundamental form of energy in the life processes. Every thought, every nerve impulse, every muscle movement, indeed every activity of any sort shown by living organisms is ultimately traceable to the release of chemical energy.

Electrical energy. Electrical energy is a result of the flow of electrons along a conductor. Electrons are the outermost parts of atoms. Nearly everyone has shuffled his feet across a rug, touched a metal light switch plate, and experienced a shock. There was a rapid flow of electrons from the metal plate to the individual on the rug. This was kinetic electrical energy. Potential electrical energy exists anywhere that a flow of electrons is possible.

Electrical energy is of great importance to man, mostly because it can be converted to other, more usable forms. For example, by offering resistance to a flow of electrons, heat is produced in the coils of an electric stove. By passing an electric current through a metal filament, electrical energy can be converted to light and heat, as in a light bulb or a toaster.

The movement of electrons is also important in living organisms. Electrons do not flow through cells in the same manner that they flow along a copper wire. However, electrons play a major role in the energy changes within living organisms. Electrochemical reactions, combinations of electrical and chemical energy, play a large part in the functioning of the brain and the rest of the nervous system.

Mechanical energy. Mechanical energy is energy directly involved in moving matter. The rolling of a boulder down a hill is an example of mechanical energy. Potential mechanical energy is converted to kinetic mechanical energy as the boulder moves from the top to the bottom of the hill. Simple machines, such as a lever or a pulley, are examples of devices designed to conserve mechanical energy and make its usage more efficient. By using a crowbar, for example, the energy expended in moving a heavy object is directed to the point where it will be used most efficiently.

One of the key features of living organisms is their ability to move independently. This movement involves the conversion of potential chemical energy into kinetic chemical energy, resulting in the contraction of muscles. Since in many organisms the muscles act upon the bones, which serve as levers, the total movement of such an organism demonstrates kinetic mechanical energy.

Radiant energy. Radiant energy is energy which travels in waves. Two well-known examples of radiant energy are visible light and heat. However, radiant energy also includes radio waves, infrared and ultraviolet light, x-rays, gamma, and cosmic rays. Most of these cannot be detected by our sense organs.

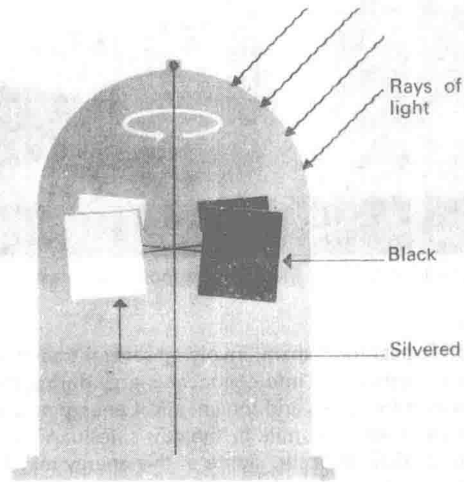
Radiant energy is used in less obvious ways than are some of the other forms of energy. In living organisms, radiant energy is useful in *photochemical* (*photo-*, light) reactions. A photochemical reaction occurs when light strikes the leaf of a green plant. A chemical compound in the leaf called *chlorophyll* is affected by absorbing certain wavelengths of light energy. This energy can then be converted by the plant into chemical energy and stored in food substances.

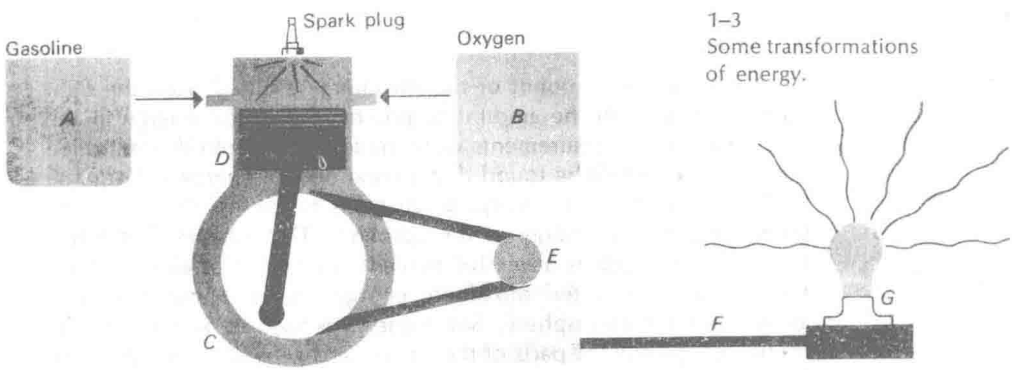
Heat energy produces its effect upon matter by speeding up the motion of the particles of which matter is composed. Heating water, for example, causes increased motion of the water molecules. If enough heat energy is supplied, boiling results. Here the water molecules are moving too fast to remain in the liquid state. They move off into the air as a gas. As we shall see, the role of heat energy in speeding up the movements of atoms and molecules has great significance to living organisms.

1–4 THE TRANSFORMATIONS OF ENERGY

All the forms of energy are interrelated and interconvertible. The conversion of one form of energy into another goes on continually. It is the basis upon which all living organisms maintain themselves. The life processes of living cells are driven by the release of chemical energy. The chemical energy may be converted into mechanical energy for motion or used to build other chemical compounds. *Energy is constantly being released and stored in living systems.*

1–2
This device, known as a radiometer, shows that light may indirectly cause matter to move. Light striking the black sides of the radiometer vanes is absorbed, and heats up this side of the metal. Light striking the silvered side is reflected. Thus this side does not heat up as much as the blackened sides. The temperature difference between the black and silvered sides causes convection movement of the air remaining in the radiometer from the cooler surface to the warmer one, building up a greater pressure on the warmer surface. Some physicists believe that the preceding explanation is not completely satisfactory. They feel that the full reason why the radiometer vanes move is yet to be explained.





1–3
Some transformations of energy.

Figure 1–3 shows the conversion of chemical energy into radiant energy from the light bulb. The fuel, gasoline (*A*), contains a certain amount of potential chemical energy. This is released when electrical energy from the spark plug ignites the gasoline-oxygen mixture. The resulting kinetic chemical energy is transformed into heat energy. The heat energy causes increased motion of the molecules of gas within the cylinder. An increase of pressure within the cylinder results, which forces the piston (*D*) downward. A wheel attached to the generator (*E*) is rotated (mechanical energy), producing an electric current along the wire (*F*). The electric current passes through the metal filament of the bulb (*G*), where it is converted into heat and light. The light energy passes to the eye of the observer, where it starts a chemical process within cells of the retina. Thus several transformations of energy have occurred.

1–4
A biological food chain, involving several transformations of energy. Radiant energy from the sun is transformed into chemical energy during the food-making process in green plants. The cow eats the grass, and the chemical energy of plant substances is converted into the chemical energy available in milk or the cow's flesh. A man drinks the milk and further energy transformations occur. Some of this energy may be converted into mechanical energy for movement. In all of these transformations, some of the energy is lost to the system for useful work. Most of the energy transformations represented above are less than 30% efficient.

How does the amount of radiant energy emitted from the light bulb compare with the amount of potential chemical energy in the original fuel? If measurements were made under carefully controlled conditions, it would be found that a great deal of energy is *lost*. The total amount of radiant energy given off is much less than the total potential chemical energy in the gasoline. The reason? The transformation of energy is never 100 percent *efficient*. Not all of the potential energy converted into kinetic energy is used. Some of it is lost as heat into the atmosphere. Some energy is used in overcoming the friction of the moving parts of the engine and generator. Much of the light from the bulb never reaches the eye. These energy losses make the process quite inefficient. Most automobile engines are less than 30 percent efficient. This means that less than one-third of the energy released from each gallon of gasoline is actually used in the forward motion of the car.

None of the energy in these transformations is actually lost in the sense of being unaccounted for. Careful measurements of energy conversions have led to formulation of the Law of the Conservation of Energy, or the *First Law of Thermodynamics*. This law states that during ordinary chemical or physical processes, energy is neither created nor destroyed. It is only changed in form. The First Law of Thermodynamics provides a useful framework for studying energy transformation in living systems. The biologist realizes that the energy an organism derives from its food is never destroyed. It is merely lost for useful work during transformation. *The success shown by some organisms in their competition with others is often due to the higher degree of efficiency with which they use the energy available to them.*