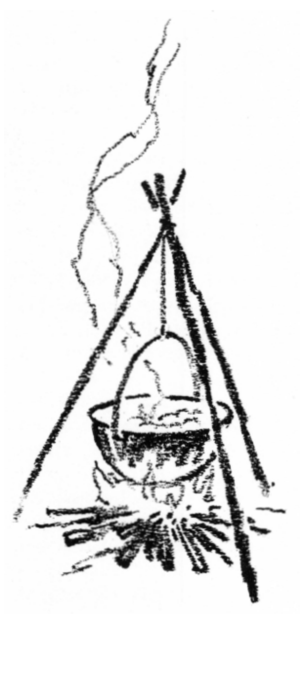
Chapter 4: Matter and Energy

"There is nothing more true in nature than the twin propositions that, 'nothing is produced from nothing' and 'nothing is reduced to nothing' ... the sum total of matter remains unchanged, without increase or diminution."

Francis Bacon
Novum Organum, 1620



Matter and energy are of central concern to the physicist. From our ability to make successful theories has come understanding of the ways in which a system may store energy and how energy may be transferred by interaction of objects or systems with one another. From this understanding has come the extensive and effective utilization of energy that is at the base of modern technology and our civilization.

Everyone forms qualitative concepts of matter and energy as a result of everyday experience. *Matter* is represented by the solid objects, liquids, and gases in the environment. Matter is tangible; it is capable of interacting with the human sense organs, and various pieces of matter are capable of interacting with one another. Matter appears to be conserved: if an object is once observed in a certain place and later is not there, you are convinced that it has been removed to another location or that it has been made unrecognizable by changes in its appearance. No one believes that it could be annihilated without a trace remaining.

By *energy* is usually meant the inherent power of a material system, such as a person, a flashlight battery, or rocket fuel, to bring about changes in the state of its surroundings or in itself. Some sources of energy are the fuel that is used to heat water, the wound-up spring (or charged battery) that operates a watch, the storage battery in an electric toothbrush, the spinning yo-yo that can climb up its string, the dammed water that drives a hydroelectric plant, and the food that results in the growth of the human body. Your experience with energy is that it appears to be consumed in the operation of the energy sources. Thus, the fuel turns to ashes and becomes useless, the spring unwinds and must be rewound, the battery needs to be recharged, the yo-yo gradually slows down and stops unless the child playing with it pulls properly on the string, and so on. At first glance, therefore, you might conclude that energy, unlike matter, is not conserved.

We will describe two operational definitions of energy in Chapter 9. In the meantime, we will use this term and refer to energy sources, energy receivers, and energy transfer from source to receiver in the expectation that you have an intuitive understanding of these concepts.

4.1 Conservation of energy

Energy transfer. When Sir Edmund Hillary and Tenzing Norgay climbed to the top of Mt. Everest, they expended a great deal of energy. Everyone knows that the two consumed food and breathed air containing oxygen to make this possible. The food, which served them as energy source, came from plants or animals that in turn depended on an energy source (plants or other animals) in a chain of interdependence that is called a food chain. Ultimately, the energy being transferred from organism to organism in the *food chain* can be traced to the sun, which produces energy in the form of light and other radiation.

Energy transfer along the food chain occurs as a result of one organism's eating another, but this is not the only mechanism of energy transfer. You are familiar with other chains of energy transfer. For instance, water escaping from a dam rushes down gigantic pipes to operate turbines, the turbines drive electric generators, and the energy is then distributed by means of transmission lines to factories and residences where some of it may be used to charge the storage battery in an electric toothbrush. The battery finally operates the toothbrush. Depending on the selection of the systems that make up the chain, energy transfer may occur from one system to another (from rushing water to the turbine) or it may occur from one form to another form in the same system (dammed water to rushing water).

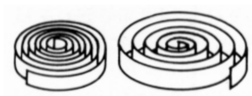
James Prescott Joule (1818-1889) was born near Manchester, the son of a well-to-do brewer whose business he inherited. He devoted himself to science early in life. At 17, he was a pupil of John Dalton, and at 22 he had begun the series of investigations that was to occupy the greater part of his life—the proof that when mechanical energy gives rise to heat, the ratio of energy consumed to heat evolved has a constant and measurable value. Joule's work had supreme significance because it solidly established the principle of the conservation of energy. It was, in Joule's words, "manifestly absurd to suppose that the powers with which God has endowed matter can be destroyed."

Historical background. During the seventeenth century, many natural philosophers studied rigid-body collisions, such as occur between bowling balls and pins. The bowler transfers energy to the bowling ball, which rolls to the pins and hopefully knocks many of them over, perhaps with so much force that they knock over other pins. The recognition of energy transfer during collisions led Huygens (1629-1695) to a quantitative study from which he concluded that the energy of motion (at that time called *vis viva* or living force, now called *kinetic energy*) was conserved under some conditions. It took many years, however, before scientists realized that the *vis viva* could be transformed into other types of energy and back again with very little loss.

James Watt developed many of the foundations of our modern concept of energy from 1763 on as he invented the steam engine and transformed it from a huge, dangerous monster into the efficient, reliable marvel powering the Industrial Revolution. Basically, the concept of energy provided a way to measure (and helped maximize) the amount of work one could get out of the coal that fueled the early railroad locomotives, textile mills and other factories. Scientists had also simultaneously been discovering the connection between "animal heat" and chemical reactions (metabolism). The third important piece of the puzzle was the recognition that the shaping and drilling of metals by machine tools resulted in a temperature rise.

These three factors inspired the physician Julius Robert Mayer (1814-1878) to speculate on the inter-convertibility of all forms of energy. James Prescott Joule then discovered the quantitative relation between thermal energy and various other forms of energy, establishing a solid experimental foundation for Mayer's theory that is still accepted today.

Since then the *law of conservation of energy* has become generally accepted as one of the most fundamental laws of nature. According to this law, energy may be changed in form but it cannot be created or destroyed. Whenever existing theories have failed to account for all the energy, it has been possible to modify the theory by including new forms of energy that filled the gap. Making these modifications is analogous to your applying the law of conservation of matter to a missing book; you include more locations in your search, and you try to remember who may have borrowed it. You do not believe the book has disappeared from the face of the earth.

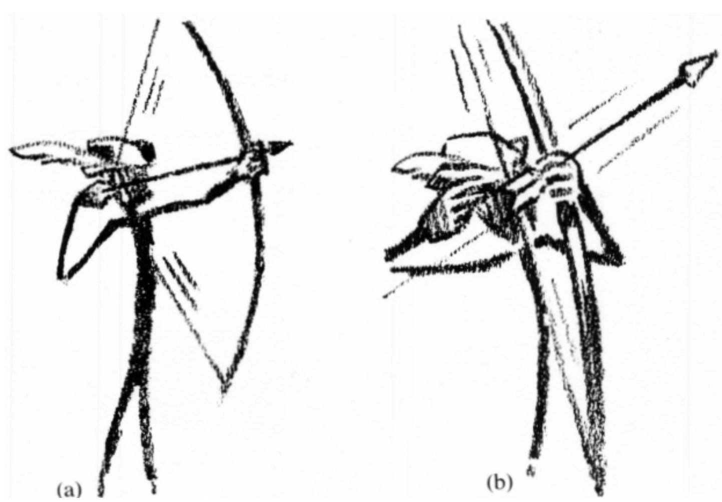


Energy storage. Because energy is conserved, it acquires the same permanence as matter. Just as material objects are kept or stored in certain containers, so we may say that energy is stored in systems (batteries, wound-up springs) that can act as energy sources. During interaction, energy is transferred from the source, which then has less energy, to one or more receivers, which then increase in energy. A system that acted as energy receiver in one process may, during later interaction, act as source and transfer to another system the energy that was temporarily stored in it (Fig. 4.1).

How much energy a system has stored depends on the state of the system. The spring in the state of being tightly coiled has more energy than in the uncoiled state. The storage battery in the charged state has more energy than in the discharged state. We will show in later chapters how the energy stored in a system is related by mathematical models to the variable factors (distance, temperature, speed, and so on) that describe the state of the system.

Energy degradation. These observations suggest that the apparent energy consumption of your everyday experience may actually be only a transfer of energy to a form less easily recognized and less easily transferred further to other systems. During the successive interactions in an energy transfer chain, some energy is transferred to receivers that are difficult to use as energy sources. Examples of these are the warm breath exhaled by Hillary and Tenzing in their climb and the very slightly heated bowling pins that become warm when their motion is stopped by friction with the bowling alley floor or walls. For practical purposes, therefore, their energy is no longer available and appears to have been consumed. In the framework of energy conservation, it is customary to refer to the apparent energy consumption of everyday experience as *energy degradation*.

Figure 4.1 Temporary storage of energy in the bow.
(a) The bow acts as energy receiver.
(b) The bow acts as energy source.



Equation 4.1
energy (initial state) $= E_i$
energy (final state) $= E_f$
energy transfer $= \Delta E$

$$\Delta E = E_f - E_i$$

Identification of systems as energy sources. When you consider the examples mentioned in the introduction to this chapter, you find that we were rather careless in ascribing energy to some of the items mentioned. The food consumed by human beings is not really an energy source capable of sustaining human activity, since it cannot by itself undergo the transformation needed for the release of energy. Instead, the system of food and oxygen is the energy source, whose state can change until the materials have been converted to carbon dioxide and water. This system has more stored energy in its initial state, before digestion and metabolism, than in the final state (Fig. 4.2 and Eq. 4.1).

You see, therefore, that a system must be properly chosen if it is to function as energy source. Just how the system is to be chosen depends on the changes that lead to a decrease or increase of the stored energy. An automobile storage battery functions as the energy source when it is used to operate electrical devices. When the battery is used in a very unusual way—when, for example, it is dropped on walnuts to break them—then the appropriate energy source includes the storage battery, the earth, and their gravitational field. The physicist's definition of systems is geared to ensure conservation of a system (Section 3.3) that functions as energy source or energy receiver. The description of the state of a system includes all the variable factors whose numerical values determine the quantity of energy stored in the system.

4.2 Systems and subsystems

When a system is thought of as energy source or receiver, it becomes worthwhile to choose as simple a system as possible so as to localize the energy. Thus, the spring is only a small part of the watch; the storage battery is only a small part of the electric toothbrush, and so on. This choice of system then will not encompass the entire phenomenon or process being investigated. A system for the entire process will include the energy sources, energy receivers, and other objects participating in the interaction of the source with the receivers. The smaller systems of objects within larger systems are called *subsystems*.

Applications. A simple application of this idea can be made to a slingshot whose rubber band hurls a stone. Both the rubber band and the stone are subsystems of the larger system including slingshot and

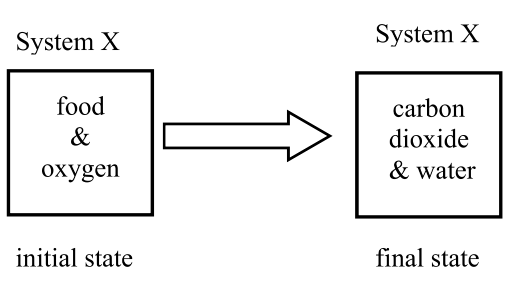
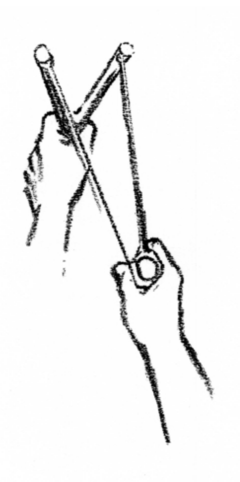


Figure 4.2 Change in the state of System X, which serves as an energy source.



stone. The rubber band acts as energy source and the stone as energy receiver in this instance.

Another application can be made to the South Sea Islander, who starts a fire by twirling a sharp stick against a piece of coco palm bark (Fig. 4.3). A system for the entire process would include the man, the stick, the bow and string, and the piece of bark. The man is the subsystem that acts as energy source. The piece of bark, which gets hot from rubbing, is the subsystem that receives the energy. The stick, bow, and string form another subsystem of interacting objects that facilitate energy transfer.

Selection of subsystems. Before concluding this section, we should add that there are often reasons other than energy transfer for selecting subsystems in a system. For instance, it may be that evidence of interaction is revealed particularly by one subsystem, as when a meat thermometer is used in a large piece of roast beef in the oven. Or, a sample of ocean water may be divided into a water subsystem and a salt subsystem. The subsystems concept is used whenever it is convenient to identify systems that are completely contained within other systems.

4.3 Passive coupling elements

In the slingshot example of the previous section, energy was transferred from the rubber band to the stone by direct interaction. In the making of a fire, however, energy was transferred from one subsystem (man) to the other (bark) through an intermediate subsystem, the bow, string, and stick (Fig. 4.3). This intermediate subsystem never acquires an appreciable amount of energy of its own. A subsystem like the bow, string, and stick, which facilitates energy transfer in a passive way, is called a *passive coupling element*.

Example. There are many situations in which there is a chain of interactions, with energy being transferred from one system to a second,

Figure 4.3 Do the important energy source and receiver in the process interact directly with one another?

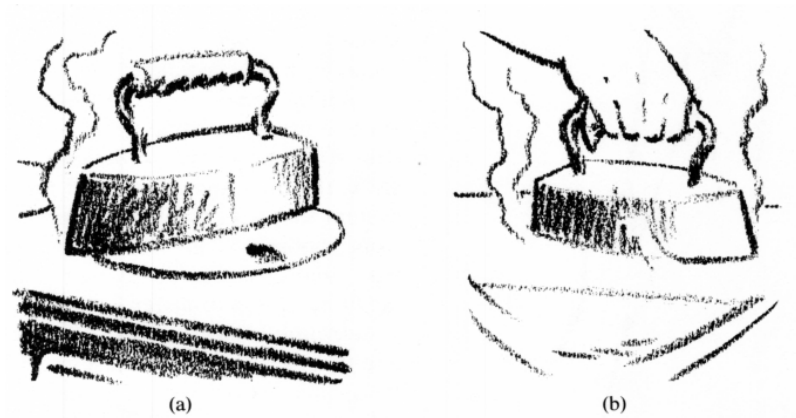


Figure 4.4 Temporary storage of energy in the old-fashioned flatiron. (a) The iron is placed on stove and acts as an energy receiver. (b) The iron acts as an energy source. What is the receiver?

then to a third, and so on. Some of the intermediate systems do not fluctuate in energy but, as it were, pass on the energy they receive as fast as they receive it. A modern electric iron is a good example. Once it has been plugged in for a time and has reached its operating temperature, the energy is supplied from the power line at the same rate as that at which it is passed on to the clothes and the room air surrounding the iron. The energy and temperature of this iron do not fluctuate appreciably. An intermediate system that acts in this way is a passive coupling element. After the iron is unplugged, however, it becomes an energy source and cools off at the same time as it heats the air; then it is no longer only a passive coupling element.

Counter-example. Some of the intermediate systems in an energy transfer chain act as energy receivers and energy sources and are not passive coupling elements; that is, their stored energy fluctuates up and down. An old-fashioned flatiron (which has no electrical heating element) is an example (Fig. 4.4). While it is standing over the fire, it acts as energy receiver and becomes hot. While it is being used to iron clothes, it acts as an energy source and gradually cools off. In other words, its energy content fluctuates along with its temperature.

Passive coupling elements. The concept of a passive coupling element is an idealization that is useful when long chains of energy transferring interactions are to be described and analyzed. The concept can be applied when the energy fluctuation of the intermediate systems are small compared to the energy transmitted. Because the passive coupling elements neither gain nor lose energy, they can be ignored insofar as measurements of energy conservation are concerned. Examples of additional systems that can be treated as passive coupling elements are illustrated in Fig. 4.5.

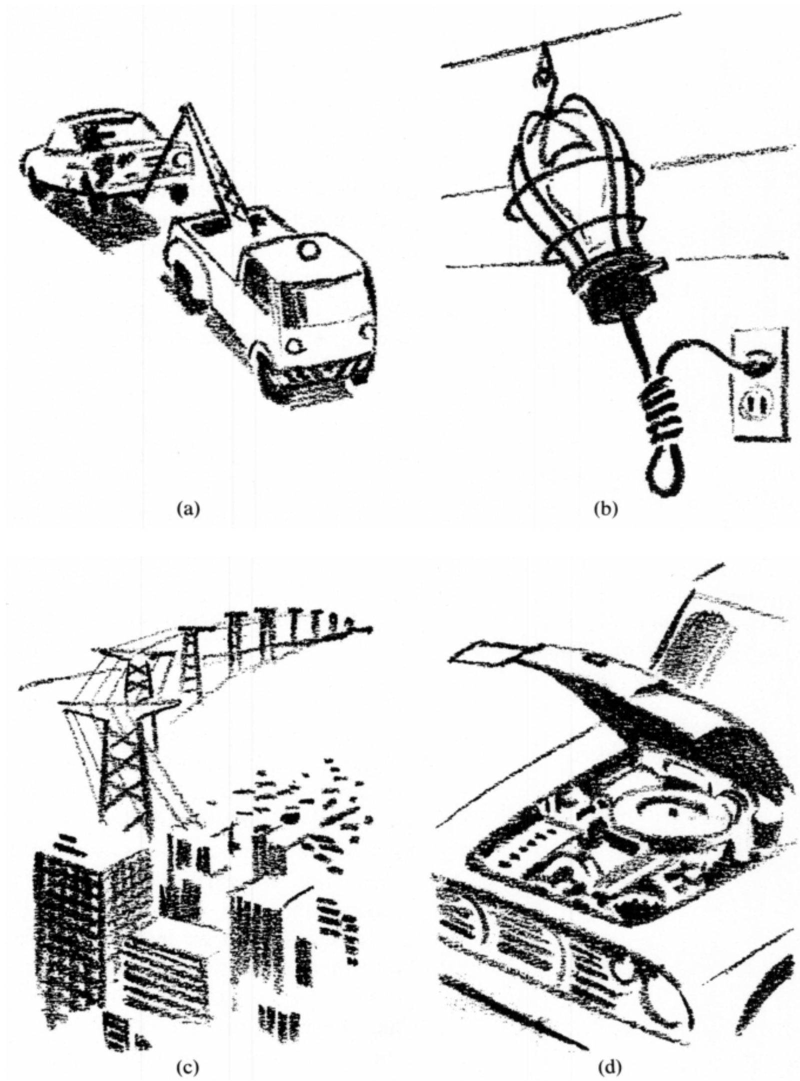


Figure 4.5 Passive coupling elements.
(a) The chain is a passive coupling element between the truck and the smashed car.
(b) The glowing light bulb is a passive coupling element between the power line and the radiated light.
(c) The high-tension line is a passive coupling element between the power station and the city.
(d) An automobile engine is approximately a passive coupling element between the exploding gasoline-oxygen system and the car.

4.4 Forms of energy storage

Consider a rubber band that is stretched and then let fly across a room. This action illustrates an energy transfer, but does not fit into the scheme of subsystems and coupling elements described in the preceding two sections. The energy is always stored in the rubber band, at first because the rubber band is stretched, and after its release because the rubber band is moving relative to the room. To differentiate the different ways in which one system or subsystem may store energy, we introduce the *forms of energy storage*. For the rubber band, we speak of two forms: elastic energy (stretched vs. unstretched rubber band) and kinetic energy (moving vs. stationary rubber band).

The concept of a form of energy storage is useful whether energy is transferred from one form to another within one system (rubber band example) or from one subsystem to another (Section 4.2). The forms of energy stored in a system are associated with the changes that can lead to an increase or decrease of the energy stored in the system. Thus, a pot of water whose temperature may drop has *thermal energy*. The food and oxygen system whose chemical composition may change has *chemical energy*. The steam that may turn to liquid water has *phase energy*. A stretched spring or rubber band that may snap together has *elastic energy*. A moving bullet whose speed can change has *kinetic energy*.

The word "phase" is used in physics with two meanings. The first refers to stages in a repeated motion, as in the "phases of the moon." The second, which we use in this text, refers to "solid," "liquid" and "gaseous phases of matter." That is, phase will refer to the three distinct "states" that matter can take, depending on the temperature and pressure.

Scientists have also discovered a fourth phase, called the "plasma" phase. A plasma occurs at extremely high temperatures, such as at the center of a star, where the particles of a gas break apart into electrically charged particles. Thus a plasma is, essentially, a gas in which each individual particle carries an excess of positive or negative charge. We will not discuss the plasma phase further in this text.

Field energy. In the forms of energy storage just enumerated, the energy was directly associated with one or more concrete objects. This is not the case when you examine systems of objects that interact-at-a-distance. Consider, for instance, the energy that is stored when a stone is raised off the ground. Because of its gravitational interaction with the earth, the stone can fall down and acquire kinetic energy. But from where does the energy come? Neither the stone nor the earth separately is the energy source here; the entire interacting earth-stone system is the energy source.

In Section 3.5 we introduced the concept of the gravitational field as intermediary in the interaction-at-a-distance between the earth and the stone. As the stone is being raised and while it falls, the gravitational field between the two objects changes. Thus, the changes of energy in the earth-stone system are correlated with changes of the gravitational field and not with changes in the stone or the earth separately. We will therefore attribute the energy of the earth-stone system to the gravitational field. In other words, we will take the view that the energy of the raised stone is actually stored in the gravitational field of the earth-stone system. This is an example of a new form of energy storage, *gravitational field energy*.

Electric and magnetic interaction-at-a-distance may be handled in exactly the same way as the gravitational interaction. Thus, a pair of interacting magnets has *magnetic field energy*, and two electrically charged clouds during a thunderstorm have *electric field energy*. The magnetic example is easiest to explore in the macro domain, since you can take two small magnets and manipulate them near each other. Your sensations suggest that the magnets are linked by a spring that pulls them together or pushes them apart (depending on their relative orientation). When you exert yourself, more energy is stored in the magnetic field; when you relax and the magnets spring back, energy is transferred from the magnetic field.

Radiant energy. In Sections 3.4 and 3.5 we described radiation as an intermediary in interaction-at-a-distance. In the example of the candle and the detector, the candle acted as an energy source. When the sun shines on green plants, the sun functions as energy source and the plants as energy receivers. In both cases, radiation carries the energy from the source to the receiver. It is therefore customary to include radiation as a form of energy, called radiant energy.

Radiant energy is similar to field energy in the sense that it is not associated with a material object or system. Nevertheless, it is necessary that you recognize radiant energy if you wish to maintain energy conservation, for there is a time interval after the sun radiates the energy and before the plant receives it. Where is the energy during this time interval? It is not stored in the sun or in the plant; if energy is conserved, it must be stored temporarily as *radiant energy*.

As we pointed out in Section 3.5, the field theory of radiation represents radiation in terms of fields that vary in space and time. In this theory, radiant energy may be classified as field energy. However, since radiant energy manifests itself quite differently from the energy stored in the fields described in the previous subsection, we will refer to radiant energy as a separate form of energy.

Examples. Several examples of how the energy transfer in some common phenomena can be described are illustrated in Fig. 4.6. In these descriptions of energy transfer we have combined the ideas of systems and of forms of energy storage by identifying the forms of energy storage that are important in each system. The idea of a form of energy storage is especially necessary, however, in those examples in which the energy is transferred from one form to another form within the same system or subsystem, as in the rubber band.

4.5 The many-interacting-particles (MIP) model for matter

The atomic model for matter. The question of what happens when matter is subdivided into smaller and smaller pieces has fascinated philosophers for thousands of years. They have also speculated about the existence of a few elementary substances, from which all others were built up. In the eighteenth and nineteenth centuries, the modern science of chemistry was established when the concepts of *element* and *compound* were given operational definitions. According to Lavoisier (1743-1794), a substance was considered to be a chemical element if it could not be decomposed into other substances by any

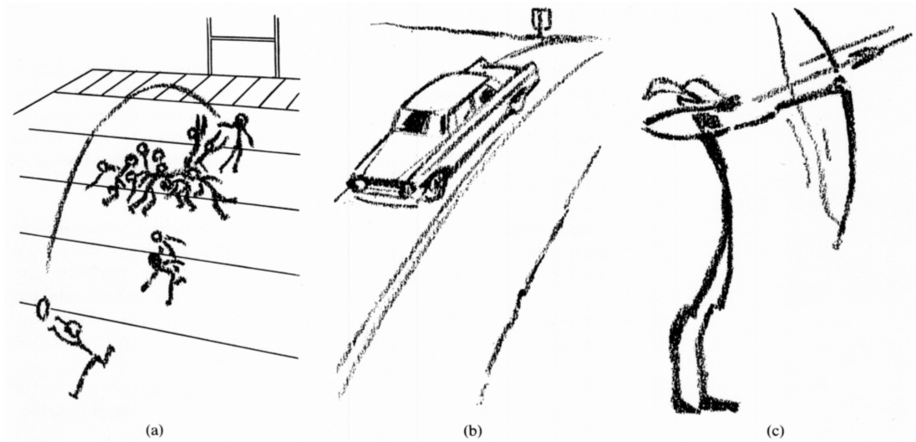


Figure 4.6 Examples of energy storage and transfer (indicates passive coupling elements).*

(a) A long pass in a football game.

System	*Type of energy storage*
passer's arm	*chemical (muscle)*
football (just after throw)	*kinetic*
football & earth system (at top of flight)	*gravitational field (& kinetic)*
football (just before catch)	*kinetic*
receiver's hands & football	*thermal (& kinetic)*

(b) Automobile coasts downhill at a steady speed.

System	*Type of energy storage*
earth & car system	*gravitational field*
*car**	*kinetic*
brake lining	*thermal*

(c) An archer shoots an arrow.

System	*Type of energy storage*
Robin Hood	*chemical (muscle)*
bow	*elastic*
arrow	*kinetic*

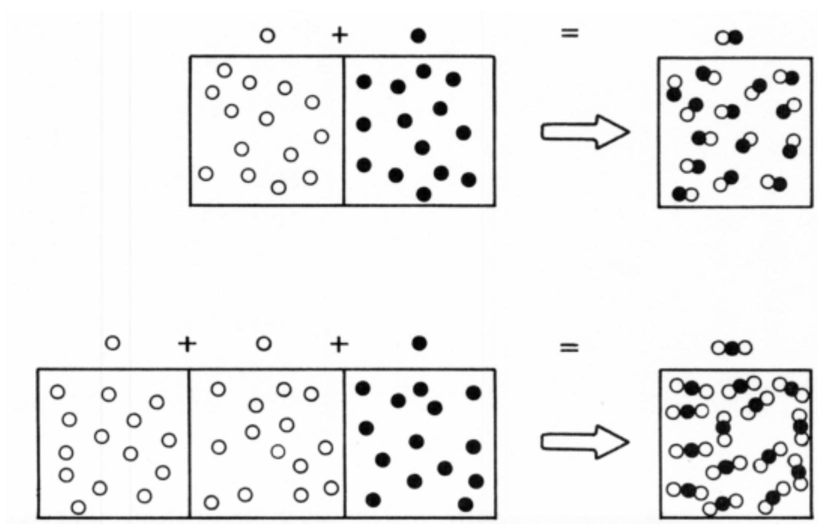
means. On the other hand, the substances that could be decomposed were considered to be chemical compounds composed of several elements.

According to this definition, a substance believed to be an element might later be decomposed by some new procedures. It would then be reclassified as a compound. Lavoisier's definition is no longer satisfactory because the development of modern techniques has made it possible to decompose even chemical elements into more primitive components (see Chapter 8). The presently accepted definition of a chemical element is based on properties that are most useful to the chemist.

Dalton's model. In the nineteenth century it became possible to make a quantitative study of the proportions in which elements combine to form compounds. It was found that elements combine in fixed proportion by weight, and that gaseous elements combine in fixed and small-number ratios by volume. These observations can be explained on the basis of the following working model, based on the ideas of John Dalton and Amadeo Avogadro (1776-1856). Elements are composed of small particles of definite weight called *atoms*; atoms combine in simple numerical ratios to form particles called *molecules*; and every volume of gas under the same conditions of pressure and temperature contains the same number of molecules (Fig. 4.7). This atomic model for matter has been remarkably successful in stimulating chemical research and in accounting, with additional refinement, for the observations made by scientists since Dalton's time.

Existence of atoms and molecules. The atoms and molecules, their interaction, and their motion make up the phenomena in the micro domain described in Section 1.2. Even though atoms and molecules were introduced originally as parts of a working model, they have been so useful in interpreting phenomena in the macro domain that almost everyone now believes that they really exist. Theories based on atoms and molecules have greatly furthered the scientist's understanding of the macro domain. Atoms and molecules are described by many specific and detailed properties, such as mass, size, shape, magnetism, ability to emit light, and so on. Mendeleev found it possible to arrange the elements in a sequence (the Periodic Table) that highlighted similarities in their chemical activity. This sequence was later expanded and slightly revised, and each element was given an atomic number according to its place in the sequence from hydrogen (atomic number 1) to

Figure 4.7 Two chemical reactions according to Dalton and Avogadro's model. Each volume of gas at the same pressure and temperature contains l4 atoms. Atoms combine in simple ratios to form new particles called molecules.



John Dalton (1766-1844) was largely self-taught. He was a retiring person, son of a humble handloom weaver, and from the age of 12 he barely supported himself as a teacher and general tutor in Manchester, England. Dalton possessed strong drive and a rich imagination and was particularly adept at developing mechanical models and forming clear mental images. His astonishing physical intuition permitted him to reach important conclusions despite being only "a coarse experimenter," as his contemporary Humphry Davy called him. Dalton's atomic theory was set forth in A New System of Chemical Philosophy*, published in 1808 and 1810.*

Dmitri Ivanovich Mendeleev (1834-1907) was a professor of chemistry at the University of St. Petersburg in the 1860's when he first noticed that the known elements could by systematized according to chemical properties. His method of classifying and arranging the elements gave us the periodic table, one of chemistry's fundamental conceptual tools. Mendeleev was a compassionate man, deeply involved in the great issues of his time. In 1890, he courageously resigned his chair in protest against the Czarist government's oppression of students and the lack of academic freedom.

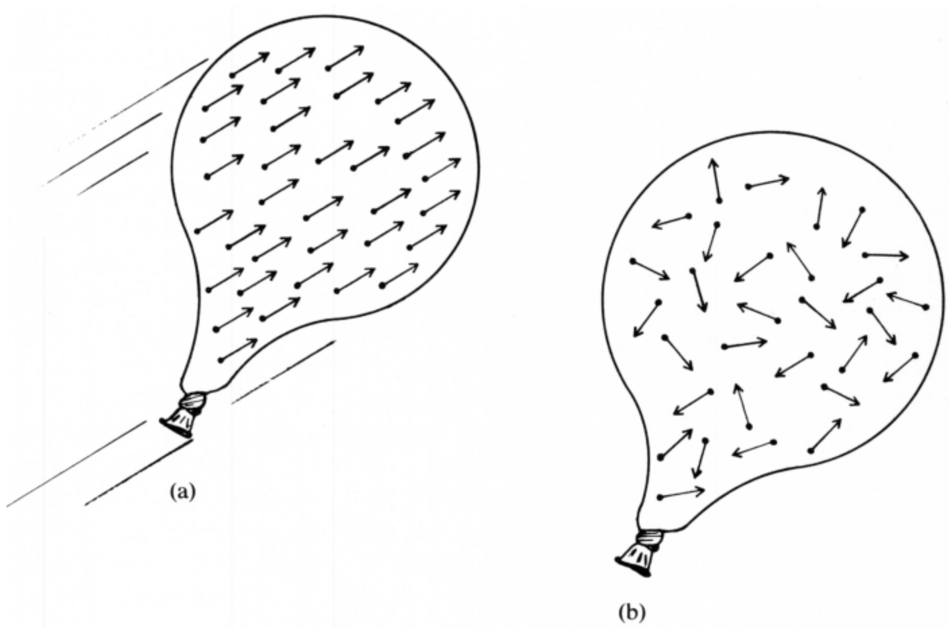


Figure 4.8 Concerted and random action of particles in a balloon.
(a) Macro-domain motion of the balloon is associated with concerted motion of the particles.
(b) Macro-domain failure to move is associated with random motion of the particles.

uranium (atomic number 92). To explain these properties, working models for atoms themselves have been invented; we will describe several of these in Chapter 8.

The MIP model. Many physical phenomena in the macro domain can be explained with the help of a working model in which matter is composed of micro-domain particles in interaction-at-a-distance with one another. The nature of the interactions, the intermediary fields, the sizes of the particles, and other details will be described in Chapter 8 but are not as important as the particles' great number and their ability to interact. We will therefore speak of the many-interacting-particles model (abbreviated MIP model) for matter. We will not identify the particles with atoms or molecules except for associating a different kind of particle with each substance. In the remainder of this section we will describe a few simple examples that illustrate the usefulness of the MIP model. Some of these will be elaborated and made quantitative in later chapters.

Random and concerted action. At the heart of the various applications of the MIP model is the essential idea that the particles are so numerous as to make the action of any single one of little consequence. Instead, only the average action or the most likely combination of actions of many particles is significant in the macro domain. The situation

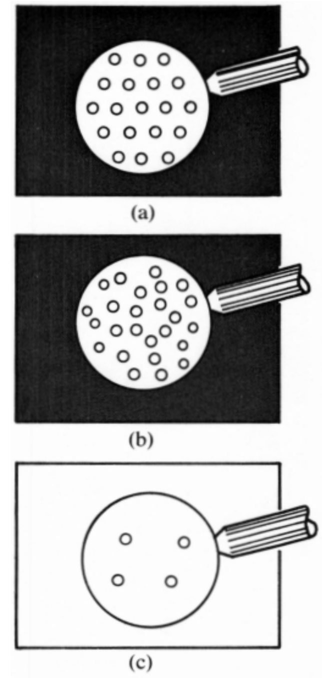


Figure 4.9 MIP model for solids, liquids, and gases.

(a) In a solid material, the particles can only oscillate about their equilibrium positions, which are arranged in a regular pattern.

(b) In a liquid, the particles can move about, but they also interact and are strongly attracted to one another.

(c) In a gas, the particles are so far apart that they rarely interact.

is analogous to that of a human mob, whose members may stampede and act in concert or may be confused and act at cross-purposes. The former is an example of concerted action, the latter of random action.

If, for instance, a blown-up balloon is thrown in a certain direction, then the particles inside the balloon move, on the average, in the same direction (Fig. 4.8a). If, however, the balloon is stationary, the particles move completely at random and their impacts with the rubber skin keep the balloon inflated but do not result in macro-domain motion (Fig. 4.8b).

The MIP model and the phases of matter. The solid, liquid, and gaseous phases of matter in the macro domain can be contrasted particularly easily by use of the MIP model. In a solid material the interacting particles are locked in a rigid pattern, and they can only vibrate a slight distance. In a liquid material the particles are in contact but are not locked into a rigid pattern; in a gas the particles are so widely separated from one another that they hardly interact at all (Fig. 4.9). This explains the rigidity of the solid, the fluidity of the liquid, and the ability of a gas to permeate the entire region of space accessible to it. It also explains the relatively low density of gases compared to solids and liquids (there are large empty spaces between the particles in a gas) and the relatively high compressibility of gases (the particles in a gas can relatively easily be forced into a smaller volume because of the spaces).

The MIP model and mixing. The MIP model also furnishes a ready description of mixing processes where several separate phases in the macro domain combine to form one phase, as when alcohol mixes with water, sugar dissolves in water, or water evaporates. According to the

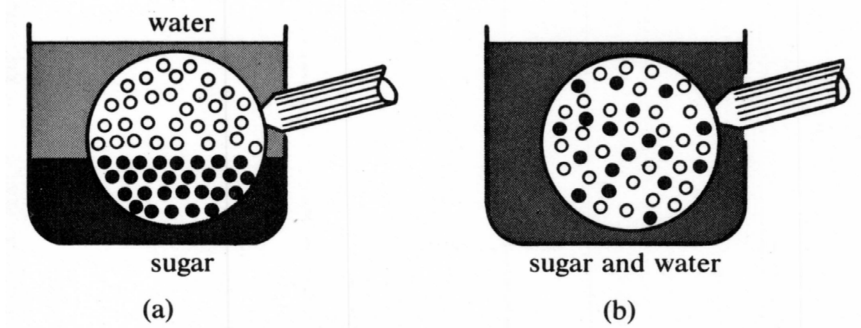


Figure 4.10 Separate sugar and water phases mix to form a single phase.
(a) Separate phases.
(b) Solution phase.

model, the particles of the separate phases mix with one another to produce the uniform solution phase, which includes particles of several kinds. Thus, sugar solution contains sugar and water particles (Fig. 4.10), humid air contains water and "air" particles. (Air is actually a solution containing nitrogen, oxygen, and several other gases, but this fact is unimportant for many physical purposes.) Thus, the interaction of separate phases that leads to solution formation in the macro domain is explained by a mixing of particles in the micro domain.

The MIP model and energy storage. A third use of the MIP model is related to energy storage. In Section 4.4 we identified seven forms of energy storage: kinetic energy, thermal energy, chemical energy, phase energy, elastic energy, field energy (gravitational, electric, magnetic), and radiant energy. These forms of energy storage are appropriate to the macro domain. With the help of the MIP model, thermal energy, chemical energy, phase energy, and elastic energy of systems in the macro domain can be explained as kinetic energy and field energy of the interacting particles (Table 4. l). In the micro domain, therefore, thermal energy, chemical energy, phase energy, and elastic energy do not have separate meanings. The elimination of these four forms of energy storage is an important unifying feature of the MIP model. We will explain how this unification is achieved in later chapters, focusing on the various forms of energy storage.

TABLE 4.1 ENERGY STORAGE ACCORDING TO THE MIP MODEL

Macro domain	*Micro domain*
kinetic energy	*kinetic energy*
thermal energy	*kinetic energy and field energy*
chemical energy	*field energy*
phase energy	*field energy*
elastic energy	*field energy*
field energy	*field energy*
radiant energy	*radiant energy*

The MIP model and interaction. A fourth use of the MIP model is to explain macro-domain interaction through properties of the particles. When two solid objects touch one another (macro domain), then the particles at the surface of one interact with the particles at the surface of the other (micro domain). The interaction that leads to the formation of solutions (macro domain) has already been described as a mixing of the particles (micro domain). When two objects interact-at-a-distance (macro domain), then some or all of the particles in one object interact-at-a-distance with some or all of the particles in the other object (micro domain). A magnet, for instance, is made up of many particles, some of which are magnets; an electrically charged body is made up of many particles, some of which carry an electric charge.

Limitations of the MIP model. Other applications of the MIP model will also be valuable. In all of them, however, it is important for you to remember that the particles of the model are not little metal or plastic balls that roll, bounce, spin, rub, and scrape the way real metal or plastic balls do. You may picture the particles as little balls, but you should be aware that such particles do not have properties beyond the ones assigned to them in the model.

4.6 Equilibrium and steady states

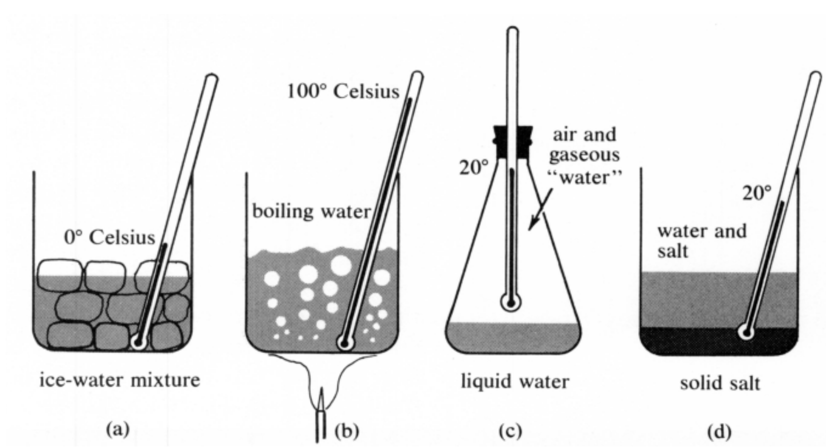
The equilibrium state. It is common experience that systems show changes in their state but that these changes do not continue forever if the system is kept in a uniform environment. A tray of water placed in the freezer, for example, freezes and eventually comes to the temperature of the freezer, but then its state does not change further. A swinging pendulum continues to swing back and forth for some time, but the length of arc of the swing decreases until it comes to rest. A flashlight operates on its battery, but after several hours the light gets dim and finally goes out.

The state of a system that no longer changes in the absence of new environmental interactions is called an *equilibrium state*. A system may come to an equilibrium state in interaction with its environment, such as the water in the freezer, or it may come to equilibrium in isolation from the environment, as did the flashlight. The equilibrium concept is applied to both cases. Since no further change of any kind takes place, no energy transfer occurs either. The equilibrium state of a system, therefore, is a state of maximum energy degradation for that system.

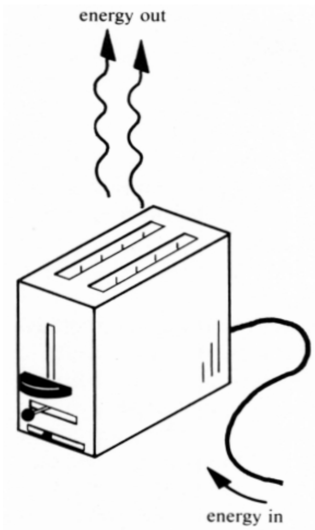
Partial equilibrium. For practical purposes, the equilibrium idea is often applied to changes with respect to only one form of energy storage at a time. In the freezer example, for instance, the equilibrium concept is applied to the temperature of the water, while motion of the water (or ice) is disregarded. In the flashlight example, the charge state of the battery is of interest, and its kinetic or gravitational field energies are not. Therefore, we speak of partial equilibrium, such as mechanical equilibrium (position and motion), thermal equilibrium, chemical equilibrium, and phase equilibrium, whenever equilibrium is reached with respect to the corresponding form of energy storage. Another example is a hot swinging pendulum bob, which may come to mechanical equilibrium (its motion stops) before it comes to thermal equilibrium with the room. Or an ice cube may melt and come to thermal equilibrium with the room air long before its water has evaporated and come to phase equilibrium as a gas mixed with the air. In all these situations, the observer's interest determines which aspect of the system he particularly notes and which details he chooses to overlook.

Phase equilibria. An especially important example of equilibrium states is phase equilibrium, in which two or more phases (solid, liquid, gas) of one substance can coexist indefinitely. At ordinary atmospheric pressure, a pure substance, such as pure water, changes from solid to liquid (melting) or from liquid to solid (freezing) at a certain fixed temperature called the melting temperature. For the substance "water," the melting temperature at atmospheric pressure is 0° Celsius on the internationally accepted scale (formerly called Centigrade) or 32°

Figure 4.11 Phase equilibria.
(a) The equilibrium state of solid and liquid water at atmospheric pressure (reference temperature for Celsius thermometer, 0° Celsius) defines the melting temperature of ice, which is equal to the freezing temperature of water.
(b) The equilibrium state of liquid and gaseous water at atmospheric pressure (reference temperature for Celsius thermometer, 100° Celsius) defines the boiling temperature of water (gaseous water is inside the bubbles).
(c) Equilibrium state of liquid and gaseous water. At room temperature (68°F, 20°C) the gas contains about 2% gaseous water and 98% air.
(d) Equilibrium state of liquid water and salt. At room temperature the liquid contains about 35% salt and 65% water.



Fahrenheit. At this temperature, liquid water and solid water (ice) are at equilibrium with one another and can coexist indefinitely. If you attempt to raise the temperature of such a system by supplying heat, the solid water (ice) will all melt before the system begins to get warmer; if you attempt to lower the temperature by removing heat, the liquid water will all solidify before the system gets colder. The melting temperature of pure solid water (ice) has been used to define a reference temperature for thermometer scales, on which it is indicated as 0° Celsius. This and other examples of phase equilibria are illustrated in Fig. 4.11.



The steady state. There are many systems that do not seem to change but that are *not* in equilibrium, for example, the heating coil of an electric toaster, which starts to glow when the toaster is turned on and reaches a steady glow after a few seconds. The state of the coil does not change any more, but the coil is continuously receiving electric energy from the power line and, at the same time, transferring energy at the same rate to the room air. The toaster coil is now acting as a *passive coupling element* between the power line and the room air. Its own state does not fluctuate, and it experiences no net change of its own energy. Such a state, in which a system acts as a passive coupling element transferring energy between other systems, is called a *steady state*. It is to be contrasted with a genuine equilibrium state, in which neither the state of the system nor the state of the system's environment is changing.

How do you tell whether a system is in equilibrium or a steady state?
1) Equilibrium systems do not gain energy from nor lose energy to their environment. Steady state systems steadily gain energy from or lose energy to their environment.
2) An equilibrium system does not tend to change the state of its environment. A steady state system generally does change the state of its environment (possibly gradually).

An exact steady state is rarely achieved in practice, but it is a useful idealization that is approximated in many practical situations. Even in the toaster example, the room gradually gets warmer and warmer. As a result, the rate of energy transfer from toaster to room is altered, with a consequent gradual change in the "steady" state of the toaster coil. The significance of the steady state is that it represents a balance between energy input and output. In the next section we will describe ways in which a steady state may be maintained, if that is a desirable objective.

Analogue models for equilibrium and steady states. Analogue models for equilibrium and steady states can be created with tanks of water. The water level in a tank represents the state of the system. The approach to equilibrium is modeled by two connected tanks of water (Fig. 4.12), with the connecting valve between them closed. Initially, all the water is stored in the tank on the left. As soon as the valve is opened, water rushes into the second tank and fills the latter up to a level that changes no further. This level represents the equilibrium state.

The steady state is modeled by a different arrangement. Only one tank is supplied with water from a faucet and the water is permitted to escape through a hole near the bottom (Fig. 4.13). Then the water in the tank reaches a level at which the water inflow and outflow are equal. This water level represents the steady state.

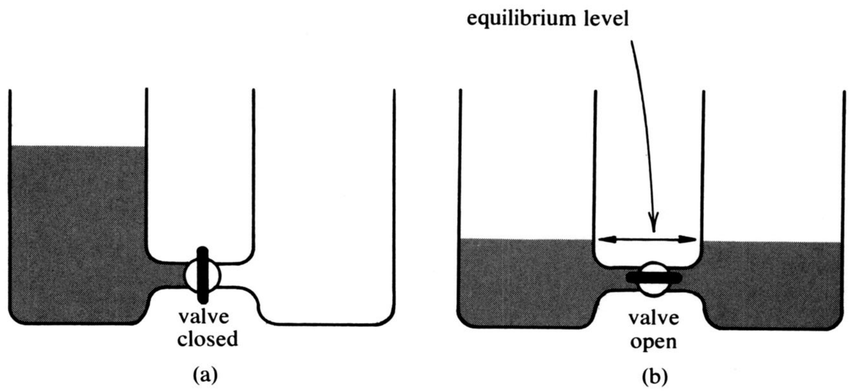


Figure 4.12 Approach to equilibrium is represented by the water level in two connected tanks.
(a) Before interaction.
(b) In equilibrium state with interaction.

Working models for systems in equilibrium and steady states. In studying equilibrium and steady-state conditions, it is frequently useful to construct working models that idealize the actual physical conditions. We took this approach in the example of the toaster, when we assumed that the slowly changing room temperature did not affect the energy output of the toaster wires. Even though real physical systems may never reach equilibrium or steady states, they often come sufficiently close so that a working model, in which certain small interactions or changes in environmental conditions are ignored, does lead to valuable predictions.

The total energy of an isolated system is conserved because the system does not interact and, therefore, does not transfer energy to any other system.

One idealized working model is that of the *isolated system*, which does not interact with its environment at all. An example to which this model may be applied is a system of ice and hot tea interacting with one another in a glass. Treating the ice and tea as an isolated system, which does not interact with the room air, enables you to predict an

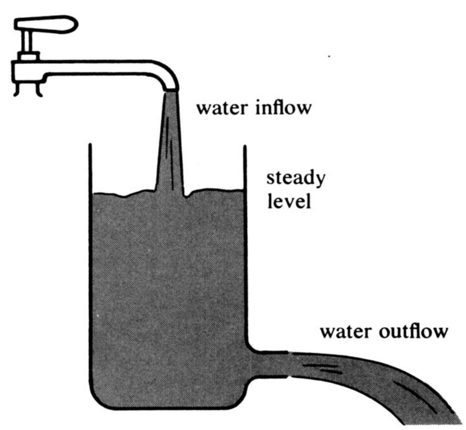


Figure 4.13 Steady state is represented by the water level in one tank with inflow and outflow

equilibrium state for the system (the temperature of the iced tea), even though interaction with the glass and the room air means that this state is approached but never reached by the actual iced tea.

A second idealized working model is that of a system interacting with an unchanging environment. Under these conditions the system may come to equilibrium or to a steady state. For example, a real sailboat on a real lake usually encounters rapidly fluctuating wind and wave conditions. Yet a boat designer will first evaluate the boat's performance in mechanical equilibrium—under a steady wind and in the absence of waves—as he determines the size of the sail, length of keel, and so on.

The temperature at any point on the earth shows great day-night and seasonal variations. By the earth's mean temperature we mean the average temperature calculated from all points on the earth's surface at one instant of time.

Applications. An important application of the steady-state concept is to the energy balance of the earth. The earth receives energy from the sun and radiates energy into space. The warmer the earth, the more it radiates. In a working model where the sun is a steady source, the earth's mean temperature will reach a steady value such that the earth's rate of energy loss through radiation is equal to the rate at which it receives energy from the sun.

The steady-state concept has many applications in other sciences as well as in physics. Food supplies remain steady as long as agricultural production is equal to consumption. Excess consumption leads to scarcity and higher prices, excess production to surpluses, lower prices, and loss of farm income. A baby's weight (and yours) increases only as long as the food it eats, water and milk it drinks, and air it inhales exceed losses through elimination, evaporation, and exhaling. When the baby's weight is steady or decreases, there is serious cause for alarm. Deer populations remain steady only as long as the birthrate is equal to the death rate. When deer are protected and their predators are killed, the population is likely to grow until other effects, such as competition for food, result in a new balance. College enrollment increases only as long as more students enter college than are graduating or dropping out. When these two rates come into balance, college enrollments will stabilize.

4.7 The feedback loop model

Stabilization of steady states. In this section we will discuss natural and man-made ways for stabilizing a steady state so that conditions are maintained despite fluctuating external influences. Among the most important natural mechanisms for stabilizing a steady state are the biological systems by means of which warm-blooded animals, including man, regulate their body temperature. A simpler but similar non-biological example is the regulation of a room's temperature by means of a room thermostat, which controls the operation of a furnace or air conditioner (or both). The thermostat ensures that the room remains at a comfortable temperature level no matter what extremes of temperature may occur outdoors.

Another example of stabilization is furnished by the trained sea lion that balances a ball on its nose by carefully timed movements of its head. Still another illustration of stabilization can be found when you drive a car in heavy traffic and try to maintain a safe distance between your car and the car in front of you in spite of changes in traffic speed. When the space in front of your car widens, your foot goes on the accelerator; when the space narrows, your foot goes on the brake.

These examples illustrate how a condition may be maintained at a steady value even though there are influences that would tend to disturb it. The intermittent operation of the furnace, the head movements of the sea lion, and your braking or acceleration have a stabilizing influence. The *feedback loop model* provides a way to analyze and understand such stabilized situations in which several interactions operate in a loop or circular pattern (Fig. 4.14).

Feedback loop systems. To apply the feedback loop model to a stabilized phenomenon that you observe, you have to take three steps. First, you have to identify the important state or condition that is being stabilized, such as the position of the ball on the sea lion's nose. Second, you have to identify the interaction whereby deviations from the steady state are detected by a system called a *detector* (the sea lion's eyes or the tactile nerves in its nose). Third, you have to identify the interaction that brings about a correction, called *feedback*, to counteract the deviation and restore the desired condition (achieved by the sea lion's head movements). Because the detection and feedback interactions are separate and distinct, the entire regulating process can be diagrammed in loop form (Fig. 4.l5), whence its name is derived.

Negative and positive feedback. The stabilizing influence we described in the specific examples came about because the feedback counteracted the deviation from steady state that triggered the detector. You can conceive of a malfunction of the coupling elements so that the feedback actually makes the deviation worse rather than counteracting it. This situation may lead to catastrophe when, for example, the car in front of you slows down and you step on the gas instead of the brakes.

There are also natural situations where the feedback enhances the deviation rather than counteracting it. When water flows off a mountain, for instance, it erodes the land to form a channel for itself. The channel is the deviation from the previously uniform mountain slope. After further rainfall, more water is gathered in the channel and it flows more rapidly down the steep walls, causing more and more erosion. The process feeds itself until the mountain is deeply eroded. In this example the water combines the roles of detector and "corrector" (by gathering in the previously formed valleys and there concentrating its erosive interaction with the surface soil). Of course, as we said above, the feedback in this example is not corrective but rather increases the deviation.

It is customary to use the term *positive feedback* in situations where the feedback enhances the deviation (erosion example). By contrast, *negative feedback* is used to denote situations where the feedback counteracts the deviation (room thermostat example). Positive feedback, which enhances the deviation, results in catastrophe or brings into play new factors that were omitted from the original feedback loop model.

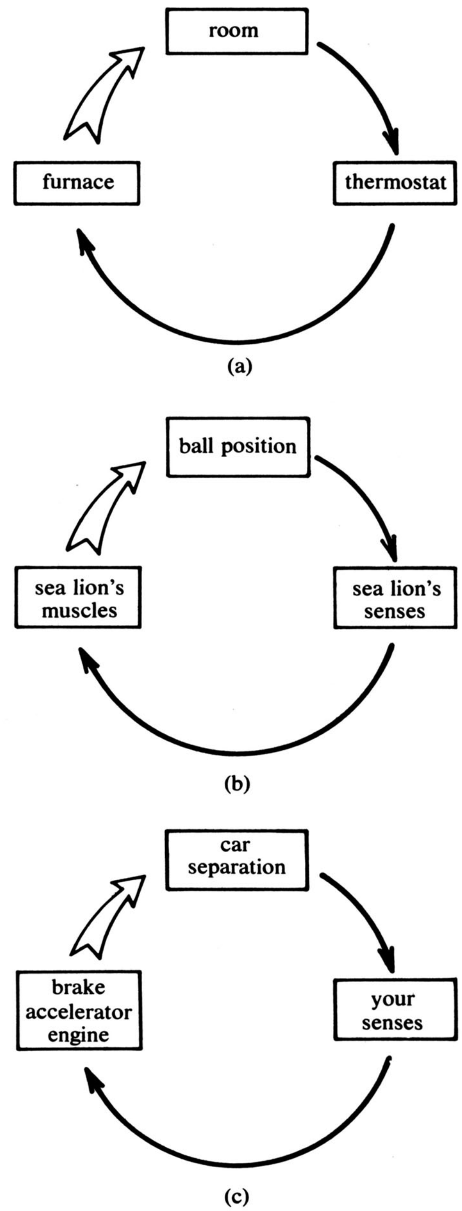


Figure 4.14 Loop or circular pattern of interactions that lead to stabilization of a steady state.
(a) Maintaining room temperature.
(b) Balancing a ball.
(c) Maintaining car separation in traffic.

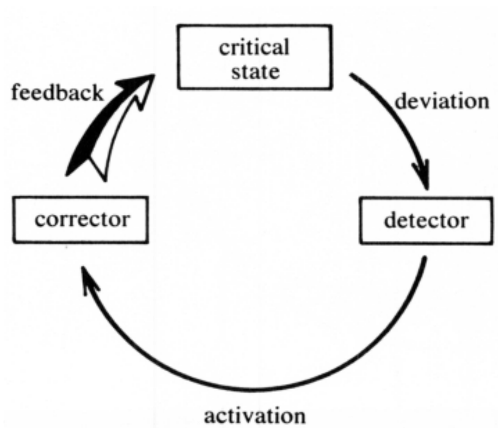


Figure 4.15 The detector identifies a deviation from the critical state. It then activates the corrector, which supplies feedback.

Feedback loop models in the social sciences. Positive and negative feedback are used in the training of animals. Psychologists use the term reinforcement rather than feedback in this context. Nevertheless, the concept is the same. For instance, consider how a pigeon is conditioned to peck at a round shape and not at a square one. Before training, the pigeon does not peck often at any shape. When it deviates from this behavior by pecking at the square shape, a "peck detector" behind the square activates an electric shock, which tends to reestablish the non-pecking behavior (negative feedback). When the pigeon deviates by pecking the round shape, however, it receives food, which tends to enhance this deviation (positive feedback) until the pigeon pecks at the round shape constantly.

Many social phenomena can be analyzed fruitfully with the aid of the feedback loop model. It is important for you to identify the steady condition of the subsystem that is at the focus of your analysis and to describe the deviations that actuate the feedback loop. If the feedback enhances the deviation, it is positive; if the feedback counteracts the deviation, it is negative. Whether positive or negative feedback is more desirable depends on your social values. Negative feedback maintains the status quo, whereas positive feedback leads to evolutionary or even revolutionary change.

Distribution of wealth. In complex phenomena, you must often consider several feedback loops, some with positive and some with negative feedback. Their net effect then depends on the relative effectiveness of the opposing feedback loops. In a social system with a fairly broad distribution of wealth, for example, laissez-faire capitalism seems to provide positive feedback for changes toward a polarized

Figure 4.16 Stabilization of a broad distribution of wealth by a negative and a positive feedback loop.

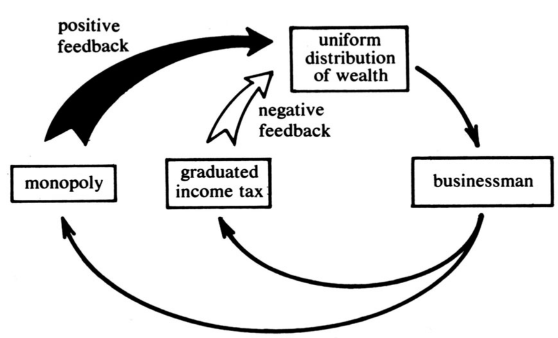
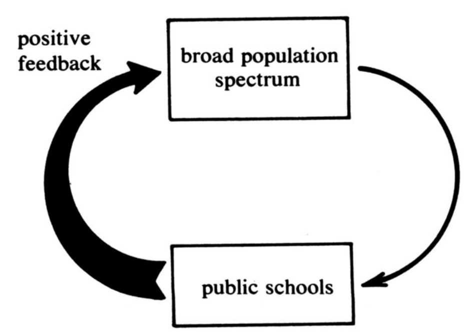


Figure 4.17 Schools can provide positive socioeconomic feedback to the population distribution in a city. When middle-class families leave the city, the schools change (decreased funding, fewer middle-class students) in a way that may repel additional middle-class residents and therefore further reduce the breadth of the population spectrum.



class structure of very rich and very poor individuals. In contrast, a graduated income tax (with higher tax rates for higher incomes) provides negative feedback for such changes and partially stabilizes the original distribution of wealth (Fig. 4.16).

Urban populations. Another currently important social feedback loop leads to the polarization of big city populations into slum dwellers and the very rich. The public schools are one of the important detecting and "correcting" subsystems here (Fig. 4.17). If the middle-class population decreases, the public schools tend to become less attractive to the remaining middle-class residents, who then tend to migrate to the suburbs in still greater numbers. On the other hand, urban schools, if they are funded and organized well enough to offer a superior educational environment, can provide negative feedback and thus contribute to maintaining, or restoring, a broad population spectrum.

4.8 Efficiency of Energy Transfer

When we use energy, we want as much of the energy as possible to go towards achieving our objective. This involves the idea of the *efficiency* of energy transfer. Specifically, e*fficiency* of energy transfer refers to the percentage of the energy from the source that is delivered to the system that we define as the intended receiver, rather than being degraded and/or transferred to other objects. For example, in a toaster, the intended receiver is the bread; the heating of the air is an unintended consequence, and the energy that ends up heating the air can be considered as degraded or "lost." Thus we expect the efficiency of a toaster to be much less than 100%. The toaster itself is a passive coupling element, which simply transfers energy and does not retain any. The total amount of energy is still conserved.

The fact that energy is degraded or considered to be "lost" does *not* mean that the law of conservation of energy is being violated; energy is *always* conserved, and the law of conservation of energy has always turned out to be true. (This is in spite of the stream of people claiming to have invented perpetual motion machines or other ways to generate energy from nothing; in fact, no such claim has ever been substantiated.). In the case of the toaster, a passive coupling element, the total amount of electrical field energy drawn from the source (the electrical utility service) can be measured to be exactly equal to the energy output, that is, the sum of the energy delivered to the toast, air, and other receivers. However, from the point of view of the *user*, the efficiency of a toaster is low because only a small part of the original energy drawn from the power source ended up in the intended receiver (the toast). We will explain efficiency of energy transfer in more detail in Chapter 16.

Summary

The conservation of energy is a powerful physical principle that leads to the concept of energy transfer. Since energy cannot be created or destroyed, all changes in the energy stored by one system must be accompanied by the transfer of energy to or from other systems. The systems that supply the energy are called energy sources, those that receive the energy are called energy receivers, and those that transmit the energy without appreciably increasing or decreasing it are called passive coupling elements.

In addition to being transferred from one system to another, energy can be transformed from one form to another. The major forms of energy storage are kinetic, thermal, chemical, phase, elastic, field, and radiant energy. The many-interacting-particles model for matter helps to explain a large number of properties of matter, including certain forms of energy storage. This model introduces a micro-domain description of physical phenomena to supplement and unify the macro-domain descriptions based on observations made by our sense organs.

The energy stored by a system in equilibrium or steady state does not change. In the former, there is actually no energy transfer between the system and its environment; in the latter there is energy transfer, but no net change because the energy input and output are equal. A system in a steady state, therefore, is a passive coupling element for energy transfer with other systems or the environment. The mechanisms by which a system maintains its steady state are analyzed most effectively by means of the feedback loop model. Negative feedback results in a stable steady state, whereas positive feedback enhances small deviations from a steady state and thereby destroys it. The efficiency of energy transfer is of interest to a user of energy; the efficiency of energy transfer is the percentage of the energy from a source has actually reached its intended receiver or been devoted to a desired end.

List of new terms

matter
energy
energy source
energy receiver
energy transfer
energy conservation
energy storage
energy degradation
subsystem
passive coupling element
kinetic energy
thermal energy
phase energy
chemical energy
elastic energy
field energy
efficiency
radiant energy
atomic model for matter
element
compound
many-interacting-particles model (MIP model)
equilibrium state
steady state
partial equilibrium
phase equilibrium
melting temperature
boiling temperature
isolated system
feedback loop model
positive feedback
negative feedback

Problems

1. Give three examples from everyday life of the apparent degradation of energy.

2. A stage magician performs many amazing tricks. Discuss two or three magic tricks as observations that appear to violate conservation of matter or energy (or both) but really do not.

3. Interview four or more children (ages 8 to 12 years) to explore the meaning they attach to the word "energy" and to the phrase "energy source." Compare their understanding with the modern scientific view.

4. Compare the meanings of the word "law" in the phrases "law of conservation of energy" and "law-abiding citizen."

5. Explain how the law of conservation of energy applies to the examples you gave in response to Problem 1.

6. Give three examples from everyday life of systems that are used to store energy temporarily. Be careful to identify the complete system and compare the state of each system when it stores energy with the state when it has no energy.

7. Consider the following statement about the bow and string in Fig. 4.l: "This intermediate subsystem never acquires an appreciable amount of energy of its own." Explain and criticize this statement. Describe one or two thought experiments that can be used to argue its validity.

8. Discuss (qualitatively) two or more of the examples of coupling elements described in the text with respect to how passive they are (i.e., how much or little of the energy they transfer is stored in them temporarily) and how much the stored energy fluctuates.

9. Give three examples (distinct from those mentioned in the text) from everyday life of systems that usually serve as passive coupling elements. Compare the three examples qualitatively with respect to how passive they are (i.e., how much or little of the energy they transfer is actually stored in them temporarily).

10. Describe how energy is stored and how it is transferred from one form to another in the following examples (see Fig. 4.6). Refer to the forms of energy storage in the macro domain. Begin each description with an energy source.
(a) The ball is kicked off during a football game.
(b) A child hops around on a pogo stick.
(c) A plugged-in electric toaster is used to toast bread.
(d) A pole vaulter vaults over a bar 5 meters high.
(e) An automobile drives up a hill at a steady speed.
(f) A tiger leaps on a mouse.
(g) A photograph is made of a snowy landscape.

11. Interview four or more children (ages 10 to 14 years) to investigate their concept of the structure and phases of matter. Evaluate their responses in relation with the modern scientific view presented in Section 4.5. (Hint: Prepare a few demonstrations where new phases are formed, such as dissolving fruit punch powder and pouring vinegar over baking soda; ask children to explain how the new phases appear from the old ones.)

12. Formulate an acceptable modern definition for "chemical element." You may consult any references you like. Classify the definition as operational or formal and give your reasons.

13. Compare the atomic model for matter with the MIP model described in Section 4.5.

14. Apply the MIP model to illuminate two phenomena from everyday life.

15. Compare the five general applications of the MIP model described in the text and rank them in order from the one that is most meaningful to you to the one that is least meaningful. Explain briefly.

16. Give two examples from everyday life of systems in (approximate) equilibrium with their environment.

17. Give two examples from everyday life of systems in (approximate) steady states.

18. Use the MIP model to construct a micro-domain description of phase equilibrium (e.g., the liquid water, air, and gaseous water in the flask in Fig. 411c).

19. Find an analogue model that clarifies the distinction between equilibrium and steady states. (See the water tank analogue, Figs. 4.12 and 4.13, as an example.)

20. Describe applications of the steady-state concept to two or three phenomena in the social sciences.

21. Describe applications of the equilibrium concept to two or three phenomena in the social sciences.

22. Construct a feedback loop model for:
    (a) the temperature of a refrigerator interior;
    (b) the light intensity reaching the retina of your eyes;
    (c) an example of your choice.
    In each case, identify the system and steady state, describe the feedback mechanism, and explain whether the feedback is positive or negative.

23. Write a critique of one of the feedback loop examples described in the text. Point out the limitations and incorrect conclusions that are implied.

24. The point is made in the text (Fig. 4.17) that public schools could provide positive feedback for changes in the socioeconomic population spectrum of a community.
(a) Apply this model to the conversion of a village into a suburb.
(b) Apply this model to an example that reveals its limitations (i.e. one for which it does not make the correct prediction).

25. Suppose you are an owner of a small store that has a certain annual income from sales as well as expenses such as rent, employees' salaries, purchase of merchandise, and taxes. Whatever is left from the income after expenses is your profit. As the owner, you might think of the percentage of the income that ends up as profit as the efficiency (or profit ratio) of your business. The income is all accounted for; none of the money disappears or is lost, but you consider part of it (the profit) as especially important, and you may want to consider how to increase the efficiency so as to maximize your profit. Compare this situation with the process of energy transfer; explain the similarities with the law of conservation of energy and with the efficiency of energy transfer.

26. Consider the process of energy transfer in an automobile: the original energy is represented by the chemical energy of the fuel; the engine transforms this energy into heat and kinetic energy and thus enables the vehicle to move from place to place. Explain how the law of conservation of energy and the concept of efficiency apply to this process. How would you expect the efficiency to be related to the number of miles per gallon of fuel? How would you expect the efficiency of an SUV and of a racecar to compare with that of a conventional automobile? What might a car designer do to increase the efficiency of a vehicle? How would you expect the efficiency to be related to the expense of running a vehicle? How would efficiency be related to the distance you could travel on a gallon of fuel? How would efficiency be related to the amount of pollution generated by the car? If you wish, find out the efficiency and miles per gallon of various types of vehicles.

25 Identify one or more explanations or discussions in this chapter that you find inadequate. Describe the general reasons for your judgment (conclusions contradict your ideas, steps in the reasoning have been omitted, words or phrases are meaningless, equations are hard to follow, . . .), and make your criticism as specific as you can.

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