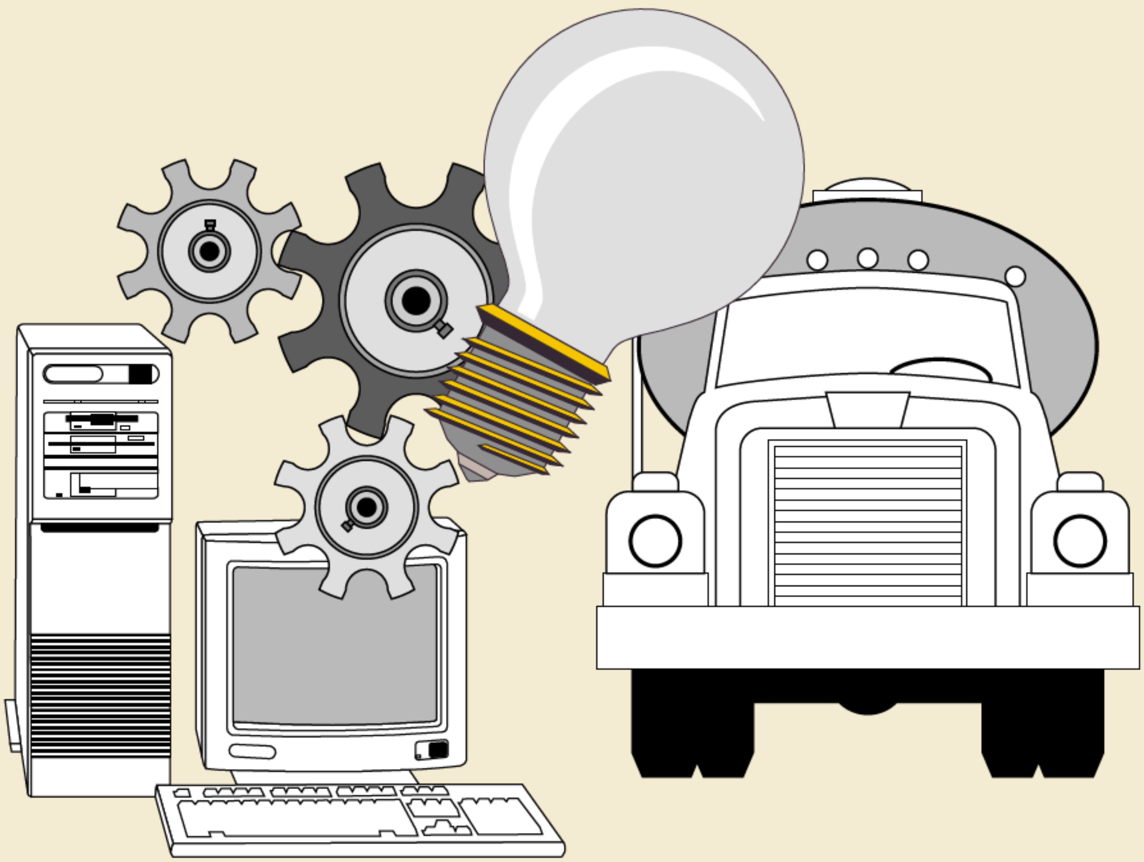
GLOBAL CHANGE
INSTRUCTION PROGRAM

Energy Use by Humans

by
Arthur A. Few



UCAR

Energy Use by Humans

by
Arthur A. Few
Space Physics and Astronomy
Rice University
Houston, Texas

Global Change
Instruction Program

Understanding Global Change: Earth Science and Human Impacts

Energy Use by Humans by Arthur A. Few

An instructional module produced by the Global Change Instruction Program of the University Corporation for Atmospheric Research with support from the National Science Foundation.

GCIP Staff

Tom M.L. Wigley, Scientific Director
National Center for Atmospheric Research

Lucy Warner, Program Manager
University Corporation for Atmospheric Research

Carol Rasmussen, Editor
University Corporation for Atmospheric Research

Linda Carbone, Secretary
University Corporation for Atmospheric Research

Advisory Committee

Arthur Few
Rice University

John Firor
National Center for Atmospheric Research

William Moomaw
Tufts University

Ellen Mosley-Thompson
The Ohio State University

Jack Rhoton
East Tennessee State University

John Snow
University of Oklahoma

For more information on the Global Change Instruction Program, contact the UCAR Communications office, P.O. Box 3000, Boulder, CO 80307-3000. Phone: 303-497-8600; fax: 303-497-8610; lwarner@ucar.edu or carolr@ucar.edu.
http://home.ucar.edu/ucargen/education/gcmod/contents.html

A note on this series

This series has been designed by college professors to fill an urgent need for interdisciplinary materials on global change. These materials are aimed at undergraduate students not majoring in science. The modular materials can be integrated into a number of existing courses—in earth sciences, biology, physics, astronomy, chemistry, meteorology, and the social sciences. They are written to capture the interest of the student who has little grounding in math and the technical aspects of science but whose intellectual curiosity is piqued by concern for the environment. For a complete list of materials contact UCAR Communications (see previous page).

Contents

Preface

Our title, "Energy Use by Humans," might be changed to "Energy Use and Misuse by Humans," except that I am optimistic that when we (all of us) understand energy, the value of the various forms of energy, and how energy flows and is transformed from one form to another, we will ultimately do the right thing. The first objective of this book is to promote and assist in the understanding of energy and its behavior.

> *We have not inherited the Earth from our fathers, we are borrowing it from our children.*
>
> -Native American saying

We hear and read a lot about the coming energy crisis; is this a real concern or a scare tactic? The crisis is very real, and in many parts of the world it is happening now; however, we really should refer to it as the fuel crisis, not the energy crisis. Energy itself is very abundant in our environment, but it is not in a form that we can easily use to do the tasks that we desire. For example, we can compute the energy released by a rainstorm that produces a centimeter of rain over a circular area with a radius of 10 kilometers. The latent heat energy that is released when the water vapor condenses into precipitation is approximately 10^{16} joules. If the rain is produced over one hour, the power generated by precipitation formation is approximately 2×10^{12} watts. The total design capacity of the U.S. nuclear power plants is roughly 100 million kilowatts = 10^{11} watts. So the rainstorm produces 20 times the power of all of the U.S. nuclear power plants combined, running at full power! We can make similar computations for solar energy, wind energy, ocean thermal energy, etc.; there is energy aplenty all around us. Our problem is that none of these sources is a good substitute for gasoline or electricity. A second objective of this book is to understand how humans use energy and explore the question of the appropriate use of energy in its various forms.

What do you guess is our worst offender on the human energy misuse list? The automobile has to be right up at the top. Of the energy available in gasoline, roughly a third is blown out the exhaust pipe as hot combustion products, which then pollute the air. Another third, roughly, goes into the radiator, which then heats the air. The final third of the gasoline's energy is used to move the automobile; while the car is moving, this energy is being lost to air friction, road/tire friction, and brake heating (whenever you use the brakes). When you are driving on a level road at a constant velocity, 100% of the gasoline's energy is going into heating the environment; the automobile and its passengers are not receiving any of the energy from the gasoline. Furthermore, the typical automobile weighs around 5,000 pounds (~2,300 kilograms), while a lone driver may weigh only 160 pounds (~72 kg); thus only 3% of the energy producing motion is used for the driver. About 1% of the energy of the gasoline is involved in moving the driver from point A to point B, and 100% of the gasoline's energy has gone into heating the environment. Not a good use of energy. A third objective of this book is to examine several of the gross misuses of energy by humans and "learn from our mistakes" how to change our behavior to become better energy consumers.

Fossil fuels—oil, coal, and gas—produce 91% of the commercial energy consumed by humans. Yet these fossil fuels are a finite resource. It's like being adrift in the ocean with only a loaf of bread to eat; at some point we will run out of bread. An oil executive speaking at an international industrial conference recently boasted, "…the energy outlook represents a genuine vein of optimism for strong development." He based this conclusion on proven oil reserves that could last 50 years. That oil executive may find optimism in a 50-year supply of oil, but I find it appalling. Modern humans (*Homo sapiens sapiens*) have existed for about 30,000 years and the fossil fuels for about 200 million years; to imagine that this entire resource will be exploited during the brief 200-year period of current history is obscene. In the next 50 to 100 years, humans will need to find replacement energy supplies for 90% of their energy needs. This is a herculean task, and if we fall short, it could be disastrous for many if not all humans. One way to make this message personal is to realize that every hour we leave a light on needlessly, we condemn a grandchild to an hour of darkness. A fourth objective of this book is to create an appreciation for the value of fuels in the energy picture and the importance of economics and policy in influencing behavior.

When we burn fossil fuels, we are releasing carbon dioxide into the atmosphere. Carbon dioxide is a greenhouse gas, which absorbs infrared radiation from the earth's surface that would otherwise escape into space; this warms the atmosphere, which radiates infrared energy back to the surface. It is inevitable that increasing the greenhouse gases in the atmosphere causes additional warming of the earth's surface. The science behind this process is undebatable; it is as certain as gravity. What is debated is how much the temperature will rise and how fast, what else is occurring in the system that is also altering the climate, and whether the historic temperature record shows increasing global temperature. A fifth objective of this book is to demonstrate that energy use by humans involves more than the energy itself; it involves the climate.

What is the solution to the looming energy crisis? We must start immediately to change the way we use fuels, and we must learn to make wise use of the abundant natural energy in our environment. There are numerous books available on alternative energy strategies and energy conservation; look for them in your library and bookstores. A final objective of this book is to point to the direction in which we must proceed in order to conserve fuels and develop the replacement energy resources needed by future human generations.

A word of caution regarding postponing action on developing replacement energy resources. Many of the technologies, materials, and resources required to develop replacement energy systems may themselves require lots of energy. Examples are the large energy costs in producing solar cells and ocean thermal generation plants. At present we have a strong global economy and sufficient energy to undertake the development of replacement energy systems. If we wait 50 years, global population growth may erode the economy and we will be on the declining part of the energy supply curve; we may not have the capability of developing the replacement energy systems that we will desperately need. We will be behind the energy eight ball.

Introduction: Energy—What Is It?

Energy and energy-related concepts such as power and force pervade our lives and our communications. We flip a switch and a light turns on. We push a foot pedal and a car accelerates. We eat, we jog, we are warmed by the sun, we watch a waterfall, we hear the surf roar. So many of the things that we perceive in our environment are manifestations of energy that it is a challenging task to try to enumerate all of them. In fact, all of our human senses function by transforming some form of energy in our environment into electrochemical energy impulses in our body's sensor cells, which are then transmitted to our brain for analysis. Our eyes see by transforming electromagnetic energy, our ears hear acoustic energy, we smell and taste chemical energy, our touch can detect heat energy and mechanical energy (pressure). We have specialized sense organs capable of monitoring all of the common energy flows in our environment; that capability is necessary to our survival.

In this book we will refine our definitions of energy in its various forms. We will explore the transformations of energy as it changes from one form to another, and we will learn that energy is conserved—it cannot be created or destroyed, only changed. Although energy never vanishes, we will learn that not all forms of energy are equally useful, and we can measure the quality of an energy form with a property called *entropy*. We will conclude by discussing energy use by humans, including the relationship of energy use to the environment and the prospects for human energy use in a world in which the human population is growing and the energy resources that we use are shrinking.

To set the stage for our formal considerations of energy, let us return to the subject of our perception of energy in our environment. If you ever have the opportunity to observe the launch of a space shuttle or another large rocket, do it. The nearly overwhelming display of power expended during the launch is an experience that you will remember for the rest of your life—the light, the heat, the earthshaking sound, the massive rocket accelerating upward. To know that people have designed and built these machines and that people, with the aid of their computers, control and direct this immense power with precision, is awe-inspiring.

In apparent contrast to the rocket launch, let us consider the flight of the male hummingbird during his territorial display. He starts his flight from a hovering position, then flies nearly straight upward at high speed to a new hovering position, from which he noisily dive-bombs real or imaginary foes in the best "top gun" style. He gains ten meters in altitude in approximately two seconds. The hummingbird's flight is impressive on its own merits, but in terms of specific power (power per unit mass) the hummingbird's two-second vertical flight is comparable to the first two seconds of a space shuttle launch. There is more to the study of energy than you may, at first, expect.

What is energy? The generic term "energy" is rather difficult to define, because energy always exists in one of its particular forms. The textbook definition of energy is the ability to do work. The presumption in this definition is that everyone is familiar with work. In fact, most people are only familiar with mechanical work. Here we will discuss energy in each of its common forms and learn that it can be transformed from one form to another.

Radiant energy includes sunlight and campfires. Heat energy is important to baking bread and forming thunderstorms. Electrical energy powers our lights, computers, and stereos. Water impounded by a high dam represents potential energy or stored mechanical energy. Gasoline, batteries, and doughnuts are all forms of chemical potential energy. The pitcher's fast ball and the wind have kinetic energy or energy of motion. Nuclear energy is invisible in nature but becomes powerfully noticeable when concentrated and released in nuclear bombs and power plants. These are examples of various particular forms of energy. For a physical property to qualify as a form of energy, it must be quantifiable and transformable. We must be able to accurately measure and/or calculate the energy, and we must be able to transform the energy to one or more of the other forms of recognized energy.

We have used the term "power" in introducing energy, but what is power? Power is the rate at which energy is being used; it is expressed as energy per second. Suppose that you want to reach the top of a hill. If you walk up the hill it may take you ten minutes, but if you run up the hill it takes you only two minutes. The energy required is the same, but the power expended is different because of the time required. Since running is five times faster, it requires five times more power. Energy and power are very similar concepts; just remember that when time is a factor in a situation it is usually power that is needed.

The Forms of Energy

Active Energy and Passive Energy

"Active energy" sounds redundant, and "passive energy" sounds like an oxymoron. Scientists talk about energy and potential energy, but there are no good generic definitions of these terms. Scientists often define them by citing particular forms of energy. So we will temporarily use the terms active and passive energy. When we observe something that is active—it is changing, or moving, or emitting—we can say that it has active energy. It is measurably active. When we see something that we know from experience can be active but that at present is not active (it is not changing, or moving, or emitting anything), we can say that it has passive energy. A burning candle has both kinds of energy. The flame has active energy; it is changing and moving and emitting. The candlestick has passive energy; there is energy stored in its chemicals, which under the appropriate conditions will produce a flame.

Active forms of natural energy are easily observed and measured because our senses have evolved to detect them—sunlight, heat, moving objects. Some forms of passive energy can be indirectly sensed, such as water stored behind a dam or a rock in balance on a cliff, but most passive forms of energy are not directly observable. The human-made or human-concentrated forms of energy frequently belie their energy content and potential hazard. A stick of dynamite provides no clue that it has greater energy content than a stick of wood of equal size. Nor does a bucket of gasoline compared to a bucket of water, or a nuclear fuel rod compared to a metal rod. We cannot with any of our senses tell whether a bare wire is electrified without testing it in some manner. Many accidents involve energy forms that are not obvious to our senses.

Work is the mechanical means of transforming energy from one form to another and of transferring energy from one system to another. Work is an active form of energy. Appendix 1, "Force, Work, and Energy," reviews these subjects and also discusses vectors; these concepts and relationships are important to understanding some of the material in this book.

Kinetic Energy

Kinetic energy is an obvious form of active energy; it is the energy incorporated in moving objects. You can understand the basics of kinetic energy just by thinking about them. Everyone recognizes that an eighteen-wheeler semi-trailer has more energy of motion than a biker moving at the same speed because of the greater mass of the eighteen-wheeler. We also recognize that the difference between driving 25 miles per hour and 50 mph is greater than a simple doubling of energy; a crash involving a car going 50 mph will do more than twice the damage of a car going 25 mph. The definition of kinetic energy, KE, for an object of mass m moving with a speed v is

$$KE = mv^2/2 \qquad (1)$$

A major league pitcher can throw a 5-ounce baseball (~ 0.14 kg) at approximately 100 mph (45 m/s). The kinetic energy of the baseball is 142 joules. The kinetic energy in a bullet fired from a small handgun is approximately 300 J. Even though the bullet has 1/20 the mass of the baseball, it has 7 times the speed. How much is a joule? It is the kinetic energy produced if you drop the baseball from a height of 2.5 feet (~ 75 cm), or if you drop a 12-oz. canned drink from a foot. It is important to remember that kinetic energy increases linearly with the mass but increases with the square of the speed. Table 1 provides representative examples of kinetic energy from a variety of everyday activities; a wide range of energy is covered in these examples.

Mechanical Potential Energy

Mechanical potential energy is passive energy, but work (active energy) is always required to generate the stored mechanical potential energy. You lift a book (mass m) from the floor and place it on the table (height h). Your muscles (using chemical energy) exert a force and perform work against the countering force of gravity (mg, where g is the acceleration of gravity); during the lifting motion the book and your arm have kinetic energy, but the book's kinetic energy goes to zero when it comes to rest on the table. Now the book has mechanical potential energy or, specifically, gravitational potential energy, GPE.

$$GPE = mgh \qquad (2)$$

Is all of the gravitational potential energy recoverable? It is all available for recovery, but the part that you can retrieve depends upon the form in which you want the energy. If you want it returned to chemical energy in your muscle then you are out of luck, because the conversion path from mechanical energy to chemical energy is long, complex, and inefficient. More on this later. All of the gravitational potential energy can be recovered by letting the book fall to the floor. Where is the energy? The energy is now (just before colliding with the floor) all in the form of kinetic energy. Designating the speed of the book as it reaches the floor as –u (downward), the kinetic energy is $KE = mu^2/2$; this is equal to the GPE of the book on the table, GPE = mgh. Figure 1 illustrates the energy exchange of the falling book.

In the discussion above we have used the concept of conservation of energy; we said that at the end of the fall all of the energy had to be kinetic energy. We are ignoring the frictional forces, which are small for this problem, but for other situations that we will consider they become important.

We can represent energy flow processes with system diagrams like the one in the next paragraph. Here, named rectangles, GPE and KE, represent reservoirs of gravitational potential energy and kinetic energy. On this diagram, "work by gravity" represents a flow of energy from the GPE reservoir to the KE reservoir. The units of "work by gravity" are power = energy/time.

Table 1
Kinetic Energy Comparisons

Object and motion	Mass (and weight)	Speed	Kinetic energy
A mass in motion	2 kg (~4.4 lb)	1 m/s (~2.2 mi/hr)	1 joule = 1 kg m^2/s^2
Small child walking	15 kg (~33 lb)	0.5 m/s (~20 in/s)	~2 J
Medium bird flying	0.1 kg (~3.5 oz)	10 m/s (~22 mi/hr)	5 J
Adult walking	70 kg (~154 lb)	1 m/s (~2.2 mi/hr)	35 J
Pitched baseball, fastball	0.14 kg (~5 oz)	45 m/s (~100 mi/hr)	~142 J
Bullet from small pistol	0.006 kg (0.2 oz)	300 m/s (~670 mi/hr)	270 J
Football player running	110 kg (243 lb)	8 m/s (~18 mi/hr)	3,520 J
Medium car on highway	1,200 kg (~2,650 lb)	25 m/s (~55 mi/hr)	375,000 J
18-wheeler on freeway	36,300 kg (~80,000 lb)	29 m/s (~65 mi/hr)	15,264,150 J

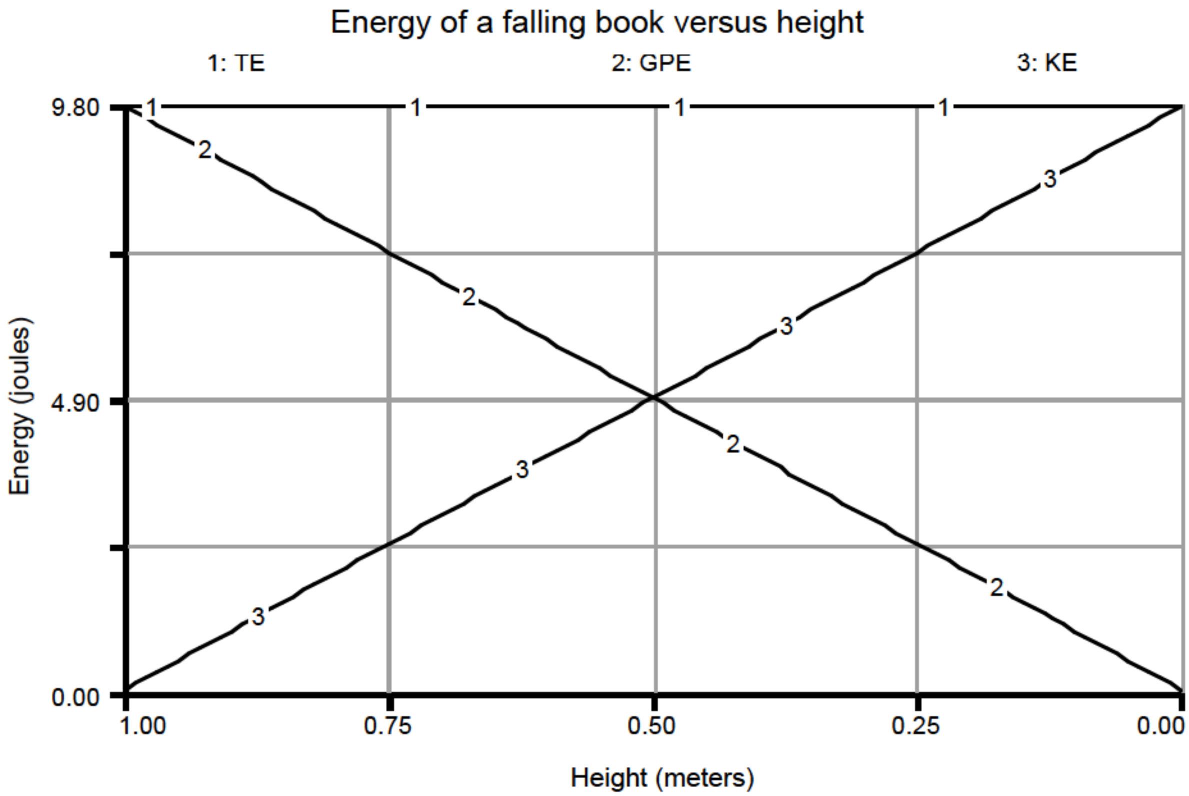
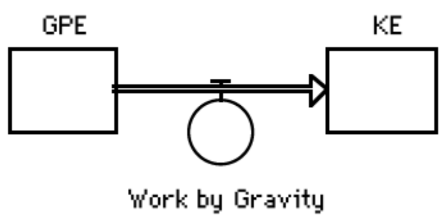


Figure 1. The total energy, TE, is the sum of the kinetic energy, KE, and the gravitational potential energy, GPE; TE = KE + GPE. As the 1 kg book falls from the height of 1 meter to the floor the gravitational potential energy (line 2) steadily decreases as it is converted into kinetic energy (line 3), which is increasing. The total energy (line 1) remains constant during the fall.

This energy system diagram is a very useful method of displaying energy conservation and energy transformations. As long as all of the energy flows connect one reser-



voir to another, the total energy of the system remains somewhere in the system. In real systems the energy system diagram will become more complex.

Another common situation in which the interplay of gravitational potential energy and kinetic energy is important is driving on a hilly or mountainous road. Your car strains slowly up the slopes but accelerates downhill without using the motor, and your brakes can become hot if used excessively to slow the car going long distances downhill. During landing, the pilots of airplanes and space shuttles must deal with the problem of excess kinetic energy gained from the descent of the aircraft from higher altitudes. On the space shuttle ceramic tiles installed along the bottom and leading edges of the wings and body are heated to red-hot temperatures by friction in order to dissipate the excess energy. You will notice that the airplane pilot lowers the wing flaps several miles from the airport during the final descent. This provides greater lift at slower landing speeds and also prevents the airplane from going too fast as it loses altitude. Downhill skiers know about the need to zigzag down steep slopes to control their speed; cross-country skiers know intimately about the "work" part of the storing of gravitational potential energy and the GPE-to-KE conversion on the downhill part of the track.

Gravitational potential energy is one form of mechanical potential energy. Stretching, twisting, and compressing springs are other ways of storing mechanical potential energy. All elastic devices such as rubber bands evoke mechanical potential energy to function. Compressed air in a tank or tire represents mechanical potential energy.

Electrical Energy

Just as the gravitational force between two masses is responsible for gravitational potential energy, the electrical force between two charged objects is responsible for electrical potential energy. The building blocks of atoms—subatomic particles—carry an electrical charge, either positive or negative. The electrical force is inherently much stronger than gravity for very small charged objects. Comparing the electrical force between a proton and an electron with their gravitational force, we find that the electrical force is 2.3×10^{39} times larger. The electrical force is so powerful that we rarely find separated charges in nature. Even in the very hot plasmas (~10^6 Kelvins, or K) in the space around the sun, where electrons are detached from protons, we find the same number of negative and positive charges; the plasma itself is neutral even though it is composed entirely of charged particles.

What about the electricity in a thundercloud? Physicists measure electrical charge in coulombs. A small, active thundercloud maintains approximately 20 coulombs of charge separated between the upper positive charge and the lower negative charge. Twenty coulombs negative is equivalent to 1.25×10^{20} electrons. This may seem like a large number, but if each air molecule in a 2/3-inch cube (5 cm^3) of air contributes a single electron, it comes to 20 coulombs. Another way to view this is that for every one charge in the thundercloud there are approximately 10^{14} neutral molecules. The thundercloud is not highly charged, but the electrical force is so strong that the energies involved are enormous.

The passive form of electrical energy requires storing separated electrical charges, Q, on a device that is called a capacitor, C. The basic measure of a capacitor is capacitance in units of farads, F. If one coulomb of charge is placed on a capacitor of one farad (i.e., one conductor has a coulomb of negative charge and the other has a coulomb of positive charge), there will be one volt of electrical potential, V, between the two conductors. The equation is

$$V = Q/C \qquad (3)$$

The properties are analogous to pouring a quantity of water Q into a vessel of capacity C. If C is large, the height of the water V will be much smaller than the height of the same quantity of water poured into a similarly shaped vessel with a smaller capacity C. Obviously, increasing the quantity of the water Q in a vessel of a fixed C causes the height of the water to increase accordingly.

A farad is an extremely large capacitance and is rarely encountered in electrical applications or in nature. If we approximate the thunderstorm described previously as a circular parallel plate capacitor of radius 2 km (~ cloud radius) and with a separation distance of 5 km (~ cloud height), we obtain a thunderstorm capacitance of 8.9×10^{-8} F, which is very small compared to 1 farad. Now when we place the 20 coulomb charge on this capacitor we get a potential of 2.2×10^8 V. That is 220 million volts, quite enough to produce lightning! (In this approximation the upper capacitor plate was at cloud top, around 10 km, for the positive charge and the lower plate at the freezing layer, around 5 km, for the negative charge. These dimensions and locations are representative of actual thunderstorms.) Small electrical charges are capable of producing large potentials when small capacities are involved. The spark that you produce to a doorknob after walking across a carpet represents tens of thousands of volts.

The active form of electrical energy involves electrical current, I, which consists of moving electrical charges and is measured in units of amperes, A, where an amp equals 1 coulomb/second.

All conductors have a resistance, R, which determines the ease or difficulty encountered by the current flowing through the conductor. A heavy copper wire will have a low resistance, and current can flow easily; the very thin tungsten filament in a light bulb will have a high resistance, which will limit the current flowing in the light bulb. The electrical force that drives the current through the conductor is derived from the electric potential, V. The equation for current is

$$I = V/R \tag{4}$$

The current is increased by increasing V or decreasing R. The current can be used to drive an electric motor to produce mechanical energy, to heat the coils in a coffeepot, to produce the radiant transmissions of a radio station, or to produce light from a lighting fixture. The electrical energy comes to us in such a versatile and valuable form that it is easily transformed into whatever form we find convenient. We can compute the power used by an electrical device, P, by multiplying the voltage across the device, V, by the current drawn through the device, I.

$$P = VI \tag{5}$$

The unit of power is joule per second (J/s), which is defined as a watt (1 J/s = 1 W). If the device behaves as a simple resistor, R, power may be computed from

$$P = V^2/R = I^2R \tag{6}$$

In this last equation we have used Equation 4 relating the current to the voltage and the resistance.

The electrical force is so strong that it is both difficult and dangerous to attempt to store it in its passive form on a capacitor; were we to do this, it would be like living in the midst of a lightning storm. In order to use electrical energy, we have devised a method of making it available without storing it. Instead we "pipe" it directly into our homes from generators. All electrical outlets and appliances in your living and working quarters are connected by electrical wires over many miles to your utility company's generating plant. Between you and the generating plant there are fuses, circuit breakers, transformers, and other devices that limit the current and offer some protection. Within these devices' limits, the full power of the electricity generating plant is accessible to you at your outlet.

Since the electrical energy is not stored, the electric company distributes power by depending on the "average" behavior of all of its customers on the electrical grid. I turn off my light at approximately the same time that you turn yours on, and my refrigerator comes on when yours goes off, etc. With many thousands of customers on an electric grid, this averaging produces a roughly uniform electrical demand on the grid, which varies only with the time of day and the season. We all know of the famous cases in which an entire interconnected grid has been "brought down" by an unanticipated event. In one recent case in the summer of 1996, a regional subgrid lost power; when it came back on it overloaded the next grid, which brought that grid down, then the next went down, etc. In a matter of minutes the whole western United States had lost power.

To my thinking, electricity is the highest form of energy used by humans. At the point of use it is extremely clean in the environmental sense. It is somewhat hazardous because of its strong force, but many safeguards are available to protect people, unless they circumvent them. If our automobiles could be driven with electricity instead of gasoline our cities would be free of most of our air pollution. However, the air pollution problem can't be solved simply by fuel substitution, since there is not enough electricity to fuel all of our automobiles. Also, some uses of electricity, such as for home heating, are not very energy efficient, as we shall see.

Nuclear Energy

The nuclear force, which holds the protons and neutrons together in the nucleus of an atom, is very much stronger than the electric force; otherwise the nucleus would spontaneously fly apart under the repulsive electrical forces between the protons. This nuclear force, however, has a very limited range of attraction and is not felt by atomic particles beyond the nucleus.

For many decades the energy community has labored to “tame the nucleus” in order to use this nuclear force (or nuclear energy) in the service of humankind. Thus far only the most crude transformation of nuclear energy (the thermonuclear fission reactor) has been successfully accomplished on the commercial scale; in these processes nuclear energy is first transformed to heat, then the heat energy is transformed into electrical energy (i.e., thermonuclear power). These transformations are not very efficient, and some of the byproducts of the process are radioactive wastes that survive, and must be stored, for millennia. The “great hope” of physicists has been in the development of nuclear fusion power, in which heavy water—water formed with hydrogen containing an extra neutron—would be the fuel for the nuclear power. (The hope stretched to hyperbole with the claim that we could burn the oceans.) There have been no successful demonstrations of nuclear fusion power generation, and the analysis of the waste

Burning rocks and water

Two very different processes can produce nuclear energy. The first process involves "splitting the atoms" or nuclear fission. Atoms of uranium have very large nuclei, which contain excess nuclear energy. These nuclei were created during an ancient supernova explosion of a large star in an environment of intense energy. These nuclei are unstable, and one by one for approximately 16 billion years they have been disintegrating into smaller stable nuclei. When they break up they release the excess energy that they have stored in the nucleus since the time of the supernova. Uranium and other radioactive minerals can be extracted from rocks and concentrated for use in thermonuclear power plants or thermonuclear bombs. Scientists learned that when the refined radioactive materials are concentrated the natural disintegration of one nucleus emits energetic particles that can cause nearby nuclei to disintegrate prematurely. The concentration, therefore, leads to a chain reaction in which many nuclei are disintegrating and releasing their intense nuclear energy. If the concentration is too high the chain reaction will "run away" and produce a nuclear explosion; this is the principle of building an atomic bomb. If the concentration is precisely controlled then the nuclear energy can be used to create steam and drive electrical generators. Nuclear energy proponents thought, erroneously, that electricity produced from thermonuclear power plants would be very cheap, so they boasted that they could produce electricity by "burning the rocks."

The second process involves the merging of hydrogen nuclei to form a helium nucleus. This process is called nuclear fusion, and, like fission, it also releases nuclear energy. The nuclear fusion process powers the sun and all of the young stars. (See *The Sun–Earth System*, by John Streete, in this series.) This process is also the energy source for the hydrogen bomb; unfortunately, scientists have been unable to tame fusion power for producing electricity. It is a challenging problem because it requires duplicating in the laboratory the conditions in the center of the sun.

Normal hydrogen atoms have only a single proton in their nuclei. An isotope of hydrogen called deuterium has one proton and one neutron in its nucleus. When two deuterium nuclei are fused they form helium, which has two protons and two neutrons, and release nuclear energy. Deuterium behaves exactly like hydrogen as a chemical, but it is twice as heavy; hence, it is called heavy hydrogen. A small fraction of all hydrogen is deuterium. Heavy hydrogen is obtained from water by refining the "heavy water"—those water molecules with one or more heavy hydrogen combined with the oxygen. This is the source of the claim that unlimited power could be obtained by "burning water."

products of a proposed fusion reactor indicates enormous problems with the disposal of the system's byproducts.

For our purposes in this module, nuclear energy is not included as a viable replacement to conventional energy resources. We may find, however, that energy crises force us to depend upon thermonuclear energy as an interim replacement energy resource.

Heat or Thermal Energy

Heat energy is simply the kinetic energy and mechanical potential energy that we discussed earlier applied to molecular-scale processes. If we think about a molecule of gas in a room, we can imagine it speeding through space with kinetic energy until it meets with an object or another molecule of gas. During the collision, part of the kinetic energy is temporarily converted to potential energy, but when the molecule bounces away, the potential energy is reconverted to kinetic energy. In a room full of gas molecules, there is continuous motion and frequent collisions among the molecules; the total kinetic energy and potential energy of all of these molecules is the heat energy contained in the room. Because of the frequent collisions among the molecules, they share equally in the available energy, at least locally. When this happens we can ascribe a temperature to those molecules, and the temperature can be related to the kinetic energy of the gas molecules; the equation is

$$\frac{3}{2}kT = \frac{1}{2}mv^2 \qquad (7)$$

in which the right-hand side is the average kinetic energy of a molecule of mass m, k is known as Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/K), and T is the ordinary temperature (in K), which we can measure with a thermometer. It seems remarkable that we can use a simple thermometer to measure the average speed of a molecule, but it is true. Sometimes very complex systems can be described quite simply if we do not need to describe the details of the system's components.

Equation 7 gives the average kinetic energy for one gas molecule; if we know how many molecules are in the room, we can multiply the equation by that number and get the total heat energy for the room. We have learned from thermodynamics that the heat energy of a homogeneous system, E, may be computed from the simple equation

$$E = C\,T \qquad (8)$$

where C is the heat capacity for the system. (Comparing these results we find that Boltzmann's constant multiplied by 3/2 is simply the heat capacity for a single molecule.) Heat energy is an unavoidable part of our environment and even our human bodies, which are maintained at a constant temperature of about 98.6 °F by essential metabolic functions. Recall how bad you feel when your body temperature rises just a couple of degrees above normal; biological systems are very sensitive to temperature changes.

Our weather, the seasons, and the climate are all products of heat energy on the larger scale. Electricity is generated by conversion of heat energy to mechanical energy to electrical energy. Almost all of the fuels used by humans (oil, natural gas, coal, nuclear, etc.) go through a heat cycle (burning) prior to conversion to the form in which they are used. (An exception to this is the fuel cell developed by the National Aeronautics and Space Administration to provide electricity on board spacecraft; fuel cells convert fuel into electricity directly without going through a heat cycle first.)

Heat energy is the lowest form of energy; when humans use energy it all ends up, sooner or later, as heat in the environment. Once degraded to heat its fate is simply to cool down to the temperature of the local environment, at which point it is no longer usable—it is dead.

Chemical Energy

Just as heat energy is the microscopic form of mechanical energy, chemical energy is the microscopic form of electrical energy. Neutral atoms, those with equal numbers of electrons and protons, produce no electric force on other neutral atoms at a distance. At very close separations, however, atoms produce local electrical forces owing to the fact that the electron distributions about the nucleus are not exactly spherically symmetric. The exception to this is the inert gases, in which spherical symmetry is maintained; these inert atoms do not react with other atoms to form molecules. The reactive atoms will form molecules according to laws of chemistry; their mutual electric attraction will form a "chemical" bond that holds them together more or less permanently, until a different environment allows a different and more favorable arrangement of molecules. The "favored" molecules in a given environment are those that are held together by the strongest electrical force. What kind of molecule is formed depends upon which atoms are available in the local environment during formation, the temperature at which the reaction proceeds, and the presence or absence of a catalyst that may act to direct the reaction process.

As we have discussed in the section on electrical energy, the electrical force is a very strong force, the strongest in nature outside the nucleus. Since the chemical bond is electrical energy, chemical energy is a highly concentrated, intense form of energy. We can get a feeling for the energy involved in chemical bonds by realizing that we must heat stable molecules to temperatures in the 1,000 K range in order to break the molecules into their constituent atoms.

Fortunately, it is not necessary to break all of the molecules into atoms before rearranging molecules and forming new molecules. If we have two different molecules, A and B, that will react with one another to form new molecules C and D, the reaction may proceed as long as the environment can supply the "activation energy" required to start the reaction. This activation energy is related to the *difference* in the bonding energies, not to the bonding energies themselves. When the stored chemical energy in the reactants A and B is greater than the stored chemical energy in the products C and D, the reaction is exothermic: energy is released in the reaction. The burning of a fuel is an example of an exothermic reaction. When the stored chemical energy in the products C and D exceeds that of the reactants A and B, the reaction is endothermic, and we must continuously supply energy to the reaction if it is to proceed. Charging a battery is an example of an endothermic process. Too frequently we think that when we are charging a battery we are storing electrical energy, but this is not the case. Batteries are storage devices for chemical energy; when we use them, chemical energy is converted directly into electrical energy, and when we charge them, electrical energy is converted into chemical energy.

Whereas heat energy is the primary driver of the physical world (weather, climate, tectonics, etc.), chemical energy is the primary driver of the biological world and the human world. Our senses, organs, and muscles all use sophisticated chemical processes that derive energy from chemicals in highly controlled reactions that allow us to lift books, throw baseballs, walk or run, and keep our bodies at 98.6 °F in summer and winter. The entire food chain is one of consuming, modifying, concentrating, and storing chemical energy.

With the exception of nuclear power plants and hydroelectric plants, it is stored chemical energy in the form of fuel that produces most of our electrical power, that warms and cools our buildings, that powers our automobiles, factories, trains, planes, etc. When we think about human use of energy, our focus needs to be on the human use of fuels, because this is where the ultimate limitation lies. There are two problems with burning fuels: one is using up a limited resource, and the other is releasing into the atmosphere greenhouse gases that produce global warming.

Electromagnetic Energy

AC Electricity

Our previous description of electrical energy did not mention the concept of alternating current, which is very important to the way some electrical systems work. A simple electrical system in which one conductor is always positive and the second conductor is always negative is called a direct current, or DC, system. Your automobile works on a 12-volt DC system in which the metal body of the car is connected to the negative terminal of the battery and alternator, and all of the electrical components (lights, starter, fans, etc.) are connected through wires leading ultimately to the positive battery terminal. The electrical systems of automobiles use the metal body as one of the power conductors between the battery and the electrical components. Current flows only between the positive and negative conductors; when touching the car body, you do not receive current unless you simultaneously touch a positive conductor.

Current in a DC system flows in one direction. In an alternating current, or AC, system, current alternately flows in two directions. The voltage applied to one power conductor relative to the other conductor continuously changes from negative to positive voltages following a sine-function amplitude that completes 60 cycles every second. Neither wire of an AC power system may be considered positive or negative since they spend equal time being both.

There may be many pros and cons to AC vs. DC electrical systems, but there is one advantage to the AC system that makes it far superior to the DC system for power distribution: transformers work only with AC systems. First, transformers can be (and usually are) built to be very efficient; only a couple of percent of the power passing through a transformer is lost to heat. Second, transformers have no moving parts, require no maintenance, and have a long expected lifetime on the power line. Third, and *most important*, transformers can change the voltage on a power line; that's what they transform—the voltage.

AC electricity is produced in the power plant by many generators in parallel producing several hundred volts. From the power plant the electrical current is carried on large conductors called busses to a transmission yard outside the plant. Very large transformers in the transmission yard convert the power from several hundreds of volts to hundreds of thousands of volts. The transmission yard is a protected high-security area because of its dangerously high voltages.

Several high-voltage transmission lines (the tallest of the power poles) lead away from the transmission yard, carrying electrical power to different areas. The end of a transmission line may be only a few miles or hundreds of miles away, but it always ends in a distribution station where transformers change the voltage from hundreds of thousands of volts to tens of thousands of volts. Again a series of subtransmission lines emerges from the station to distribute power to substations of the power grid. Each subtransmission line will end at a substation where transformers convert the voltage down to thousands of volts for distribution to individuals or neighborhoods.

The voltage most commonly used in our neighborhoods (on the power poles in our streets and alleys) is either 14,400 V or 7,200 V; this is much too high a voltage to bring into buildings. Somewhere close to every user there will be one final transformer. For overhead service the transformer will be mounted on the power pole usually within half a block of the user; for underground service the transformer will sometimes be installed inside a locked steel case on a concrete pad above ground.

For a residence, the voltages produced by this final transformer are 240 V and 120 V on a three-wire service. What this means is that there are two power wires (hot wires) and one neutral wire. The voltage between the two hot wires is 240 V, and it is used for large electrical appliances such as air conditioners, ranges, clothes dryers, etc. The voltage between either hot wire and the neutral is 120 V; all of the smaller appliances, lights, and receptacles (outlets) in the residence are connected between a hot wire and the neutral providing 120 V. The electrical contractor who wired the building divided the various circuits in the building to create an equal load on both hot wires.

So there we have it: wires and transformers covering many miles, and the voltage being stepped up, then stepped down; pure electrical energy at the correct voltage instantly accessible without any storage devices in the system. But it could not work without the transformers, and transformers will only work with AC electricity.

You might wonder why the many different voltages are necessary; why doesn't the utility simply generate electricity at 120 V and distribute it directly to the user at that voltage? This doesn't work because the wires have resistance, and the power loss in the wires is I^2R (resistance times the square of the current). When the current finally reached the customer, the voltage might only be 10 V and the wires would be warm from the heat produced. Since the available power is given by VI (voltage times the current—see p. 7), by going to a higher voltage we can transmit the same power with a smaller current. These relationships tell us that if we double the transmission voltage we can halve the current and reduce the line resistive loss by a factor of four! So, the rule of thumb for electrical power systems is to keep the voltage as high as possible for as long as possible (consistent with design capabilities and safety). This design principle not only minimizes the line losses, but it also produces the most constant voltages for the user. It is the transformers that make all of this possible.

The magnetic force and the important role that it plays in motors, generators, and transformers is described in Appendix 2, "Magnetics."

The three-pronged plug

In older U.S. construction the electrical wall receptacles have two slots; in newer construction the receptacles have the two slots plus a third circular hole, which mates with the three-pronged plugs that come with most modern appliances. The third wire that connects to the circular plug is called the grounding wire, and its purpose is to open a circuit breaker or blow a fuse in the event of a short circuit. Under normal conditions the third wire carries no current; the two power wires connected to the two slots carry all of the normal current.

Antennas and EM Radiation

The familiar form of an antenna is a metal rod that radiates or receives radio waves. We see them on cars and trucks, and we see the more complex TV antennas on housetops. We will take a more general view of antennas here, because many human-made and natural objects behave like familiar antennas when emitting or receiving electromagnetic radiation.

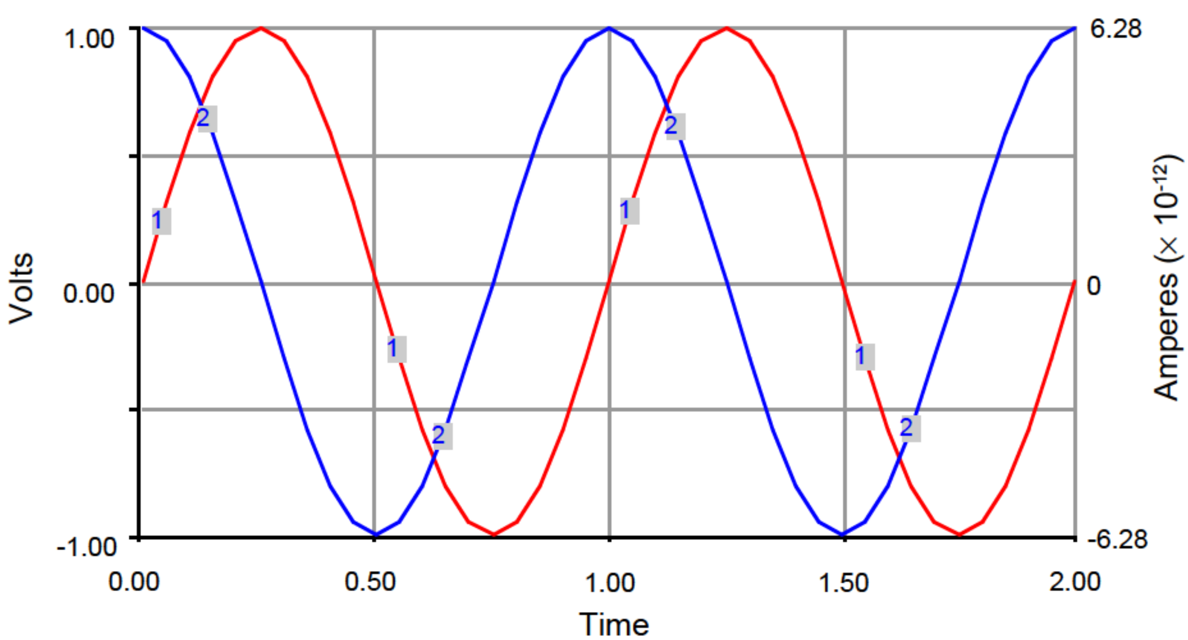
Electric charges emit electric fields. Every time an electric charge moves (current), a magnetic field is created around the moving charge, and every time a magnetic field changes it exerts a force on electric charges, causing them to move (current). Electricity and magnetism are two parts of the same phenomenon. The back-and-forth movement of charges creates combined electric and magnetic fields that propagate outward from the source and carry energy with them through space. These waves are electromagnetic radiation. Like ocean waves, electromagnetic waves have peaks and troughs corresponding to the maximum and minimum values in the fields. They can be described by three characteristics: speed, wavelength, and frequency. Speed is measured by how fast the peaks move forward, wavelength by the distance between peaks, and frequency by how many peaks pass a point in a second.

A simple radiating antenna is a short wire connected to an AC generator of electricity, with the other side of the generator connected to the ground. The other end of the short-wire antenna wire is not connected to anything, but there is a small capacitance, C, between the wire and the ground. If the AC source has a voltage, V, then the antenna must by Equation 3 have a charge $Q = VC$. As the AC generator alternates between positive and negative voltages, the antenna will be charged first positively then negatively, going through zero between each cycle. A small AC current must flow from the generator to the antenna to supply the charge on the antenna (Figure 2). When charged, the antenna emits an electric field, and when the current flows in the antenna the magnetic field extends from the antenna. With the proper instruments the electric and magnetic fields can be sensed in the space around the antenna.

The electric and magnetic fields created in the space around the antenna oscillate in a sinusoidal manner at the same frequency as the AC generator that is driving the antenna. Actually, these fields propagate away from the antenna at the speed of light, c; these propagating electric and magnetic fields are called electromagnetic (EM) waves. If the AC generator has a frequency f, then the waves will have a wavelength λ, where $\lambda = c/f$. Remember the wavelength is the distance between two adjacent peaks in the wave, and the frequency is the number of peaks that pass by you each second. As the frequency of the AC generator increases, the wavelength becomes shorter and the efficiency of the simple antenna in radiating EM waves increases. Although an antenna of length L will radiate EM waves at all frequencies, it is only highly efficient when $L = \lambda/2$. At that frequency the antenna creates a standing wave. Standing waves are created by two identical waves propagating in opposite directions; the combination of the two propagating waves appears like a stationary or standing wave. Most musical instruments work on this principle—sound waves run back and forth along a violin string or in a flute to form standing waves and propagate into the air beyond the instrument. The frequency of the sound wave, its tone, is that of the standing wave plus harmonics. A similar thing occurs with the antenna; a standing wave is generated and an electromagnetic wave propagates outward from the antenna.

Electromagnetic waves are emitted and absorbed by many objects other than simple antennas: atoms, nuclei, solids, free charges, etc. The "effective antenna" concept is useful in visualizing these interactions. What size antenna is needed to interact strongly with ultraviolet light? Ultraviolet light has a wavelength as short as 3×10^{-9} m; we should

Figure 2. Curve 1 depicts the voltage that the AC generator applies to the antenna. The shape of this curve is called sinusoidal; it is symmetric in its positive and negative parts, and it is periodic (repeats itself exactly), with period equal to 1 time unit in this example. The antenna current, curve 2, is also sinusoidal but it is shifted in time with respect to the antenna voltage by 0.25 time units, or 1/4 of the period. This is a 90° phase shift since 1/4 of 360° (a complete circle) is 90°.



look for an antenna of length L ~ 10^{-9} m. When we look for objects in nature in this size range we find molecules. We expect that ultraviolet light interacts with the atoms and molecules. Indeed, we know that it is the ozone molecule that absorbs ultraviolet light in the ozone layer. A better understanding of how atoms and molecules interact with electromagnetic radiation is obtained from quantum physics. A good source for this discussion is *The Sun–Earth System*, by John Streete, in this series.

Electromagnetic radiation, both natural and human-made, is pervasive in our environment. Some natural examples are sunlight and lightning; human-made examples are emissions from power lines, radio and television transmissions, microwave ovens, and cellular telephones. Table 2 lists examples of electromagnetic radiation that span from kilometers (1,000 meters) to micrometers (a millionth of a meter) in wavelength. For the shorter-wavelength radiation such as light the "antennas" involved are electrons changing their energy state in atoms.

Note that a $\lambda/2$ antenna for a power line is approximately the width of North America, but before jumping to the conclusion that such an antenna is impossibly large we must understand that the power grids of the United States and Canada are all interconnected and synchronized. Indeed, the North American electrical power transmission grid could be viewed as a complex antenna for emitting electromagnetic radiation at 60 cycles per second (60 Hz).

Table 2

Type	Frequency	Wavelength
Power lines	60 Hz	5,000 km
AM radio	~1,000 kHz	~300 m
FM radio	~100 MHz	~3 m
Television	~600 MHz	~0.5 m
Microwave	~30 GHz	~1 cm
Infrared	~3×10^{13} Hz	10 µm
Visible	~6×10^{14} Hz	0.5 µm
X-rays	~1×10^{18} Hz	3×10^{-10} m

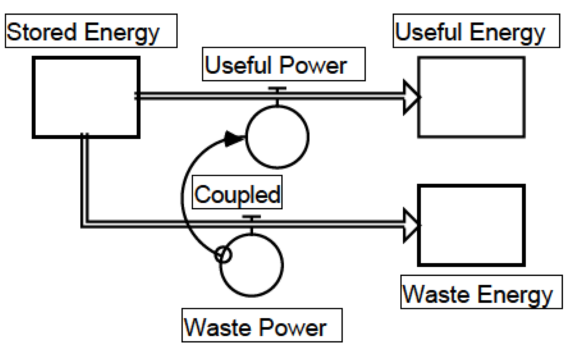
Electromagnetic radiation can be converted to other forms of energy. Visible sunlight is absorbed by dark pavement and is directly converted to heat energy. If that same light strikes a field of snow, the energy is mostly scattered or reflected. If it falls on a forest, certain chemical compounds in leaves will convert selected frequencies of radiation into chemical energy in the process we know as photosynthesis.

We may think of these conversion processes as atomic-sized radio receivers with the electrons representing the receiving antennas. In some materials such as conductors some of the electrons are free to move about between the atoms of the material and may respond to electromagnetic radiation at many different frequencies by oscillating with the wave. If the electrons encounter friction or resistance by colliding with atoms in responding to the radiation, their energy will be absorbed; if there is little friction the electrons will oscillate and become an antenna for reradiating the electromagnetic radiation. Very good conductors like silver when highly polished become good reflectors—they reradiate light. A mirror reflects not because of the glass but because the back surface of the glass has a thin coating of silver. Poor conductors like carbon absorb most visible radiation (light) by converting the motion of the electrons into heat; hence carbon appears black. Nonconducting materials such as glass and some plastics have no free electrons or movable electrons attached to atoms; when electromagnetic radiation encounters these materials it passes through them. Most common materials are mixtures of compounds, some of which have bound electrons that can be moved to different energy levels in the compound. These electrons act as selective antennas that respond only to electromagnetic radiation of specific frequencies. When we observe color in materials illuminated with white light it is the action of these selective compounds.

Energy Transformations and Efficiency

Required Waste Power

When humans use energy, they follow the general principle depicted in the illustration below. We have a passive energy source, usually a fuel, from which we withdraw "useful power" with some device that transforms the energy from one form to another. Inextricably and unavoidably some of the energy is also transformed along another path, "waste power." It would be great if all of the transformed energy could be converted into the "useful power," but the laws of nature prevent this; nature requires that part of the power produced must be waste power (more on this later).



Efficiency measures the fraction of the total energy (or total power) that becomes useful energy (or useful power) in the transformation process. The definition for efficiency is

$$\text{Efficiency} = \frac{\text{Useful Power}}{\text{Useful Power} + \text{Waste Power}} \quad (9)$$

The average efficiency over an extended period of processing the transformation may be found from a similar expression,

$$\text{Average Efficiency} = \frac{\text{Useful Energy}}{\text{Useful Energy} + \text{Waste Energy}} \quad (10)$$

Obvious causes of waste energy are friction in mechanical systems, resistance in electrical systems, and heat loss from thermal systems; we call these dissipative losses, because they dissipate, or squander, energy. These losses can be reduced but never eliminated by using better bearings, larger wires, and increased insulation. There are, however, other forms of waste power that are more fundamentally connected to how the system works, and they are not easily eliminated. In the drawing above, the curved arrow linking Waste Power to Useful Power and labeled Coupled represents those forms of waste power that the system requires to function; we will refer to these as the "Required Waste Power." The best way to understand required waste power is to examine how several systems actually work and find the required waste power for the systems.

Our first example is a well with an electric pump that lifts water into a storage tank. When the pump is running, water is moving upward in the pipe to reach the storage tank; the useful power in this system is the power used in lifting the water from the well upward against the force of gravity to reach the tank. The water moving upward in the pipe has velocity and, therefore, has kinetic energy; the required waste power in this system is the power being supplied to move the water, its kinetic energy. (Upon reaching the tank the kinetic energy is transformed into turbulent energy and finally through friction into heat. Turbulent energy is the kinetic energy in the swirling motion of the water in the tank.) The useful power and the required waste power are coupled; you cannot fill the tank without moving the water and wasting some of the energy.

We use the equations in the box on the next page to create a mathematical model for the pump; the results are displayed in Figure 3.

The flow, F, in a pipe of inside diameter, d, is measured in cubic meters per second or the more familiar gallons per minute, where

$$1 \text{ m}^3/\text{s} = 15{,}850 \text{ gallons/minute}$$

We can obtain the flow from the product of the cross-sectional area of the pipe, $A = \pi (d/2)^2$, and the velocity of the fluid, v:

$$F = Av$$

For each second of pump operation a volume of the fluid equal to the flow must be lifted a height, H, from the well into the tank. The power required to lift the fluid, P_L, is

$$P_L = \rho gHF$$

where ρ is the density of the fluid and g is the acceleration of gravity.

For each second of pump operation a volume of fluid equal to the flow must be accelerated to the velocity v; the power required to impart kinetic energy of motion to the fluid is P_M, where

$$P_M = (1/2)\, \rho v^2 F$$

The pump efficiency, E_p, will be

$$E_p = P_L/(P_L + P_M)$$

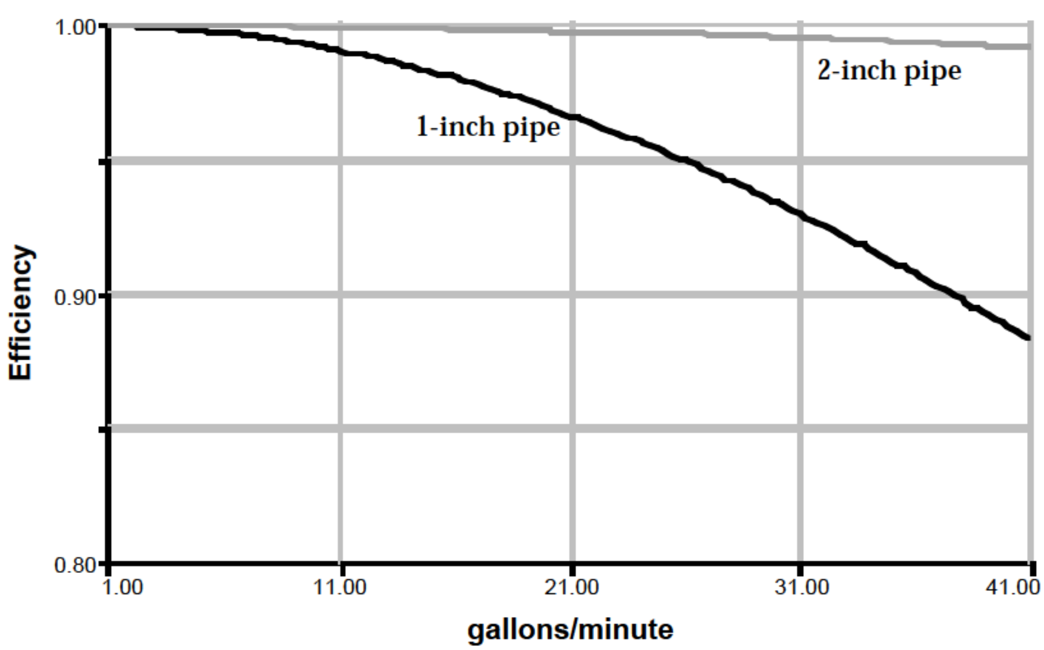
when we ignore friction and electrical resistance.

In the model for the pump system, we have used the following parameters: H = 10 meters (~32 feet), d = 1 inch (solid line) or 2 inches (dashed line), F = 1 gal/min to 41 gal/min. (An outdoor water faucet fully open flows at roughly 10 gallons a minute.)

The pump example exhibits several characteristics of general energy transformation systems. We see that at very small flow the system is very efficient, but as we increase the demand (larger flow) the efficiency rapidly decreases. This is because the useful power (P_L) is proportional to the velocity (F = Av), but the required waste power (P_M) is proportional to velocity cubed. The power lost to friction and the power lost to electrical resistance have a similar relationship to the velocity; if we had included them in the model, the curves in the graph would look much the same but the values for efficiency would be lower. If we were to model an electrical transmission system or an automobile we would get a similar result; increasing the demand decreases the efficiency substantially.

The second system characteristic that we see on the graph is that the two-inch pipe is much more efficient than the one-inch pipe. This is

Figure 3.



because the flow is proportional to the cross-sectional area of pipe, and when we double the pipe diameter we decrease the velocity by a factor of four for the same flow value. Increasing the diameter also decreases the friction. The performance of the system is better in all aspects when the pipe diameter is increased, so why aren't the larger pipes always used? They cost more.

This brings us to the third system characteristic that is exemplified here. More efficient systems can be built if we invest more resources in the original design and construction. We have developed the bad habit of trying to keep up-front costs as low as possible; this frequently means that we pay a lot more in the long run.

Our second example will reverse the processes of the first. We have water impounded in a lake behind a dam. Water is allowed to run through a large pipe to a turbine, which turns a generator, which makes electricity. We start with gravitational potential energy in the water, which is converted to kinetic energy in the water, turbine, and generator, which in turn generates electrical energy. This sounds pretty straightforward.

Now, what happens to the water as it leaves the turbine? If it doesn't continue moving it will stop the turbine, because the water behind it will have no place to go. It's pretty simple once you think about it; the water coming out must retain some of its original kinetic energy or the system will not work. The power in the water coming out of the turbine is the required waste energy, and the electrical power is the useful power; these two powers are coupled by the basic design of the turbine.

The power produced by the water is proportional to the height of the water above the turbine and to the flow. The required waste power here, P_O, is proportional to the flow cubed and inversely proportional to the output orifice area squared (recall $F = vA$). Increasing the area of the output orifice increases the efficiency without decreasing the turbine power, but there is a limit to the output area, which is fixed by the area of the turbine blades.

The total power available for the input flow into the turbine, P_I, is

$$P_I = \rho g H F$$

This is the same equation that we had for the power of lift for the pump in the previous example, except here it is the power in the water pressure ($\rho g H$) at the bottom of the lake. We can use the equation for the kinetic energy of motion from the previous example to obtain the energy in the outflow from the turbine,

$$P_0 = (1/2)\,\rho v^2 F$$

where v is the velocity of the water coming out of the turbine. We can write the efficiency equation by subtracting the output flow power from the total available energy

$$E = (P_I - P_0)/P_I$$

Substituting and simplifying we get

$$E = 1 - (v^2/2gH)$$

This can be written as a function of the flow

$$E = 1 - (F^2/2gHA_0^2)$$

where A_0 is the cross-sectional area of the output orifice to the turbine and $F = vA_0$.

Figure 4 shows the electrical power produced and the efficiency as a function of flow.

This model uses $H = 50$ m and $d_0 = 24$ in.

As we have seen in the previous example, efficiency can best be obtained by investing in the original design and construction.

As before, we see (1) that increasing the demand on the system decreases the system efficiency, (2) that the system can be designed to be more efficient (larger turbine blades and output orifice), and (3) that the initial cost for a more efficient system will be greater but should produce a long-term payback.

There are important lessons to be learned in these examples that have general application to many energy transformation systems. The required waste power is strongly coupled to the system's performance because energy transformation systems usually involve flow of a fluid, an electric current, or heat. Our turbine will not

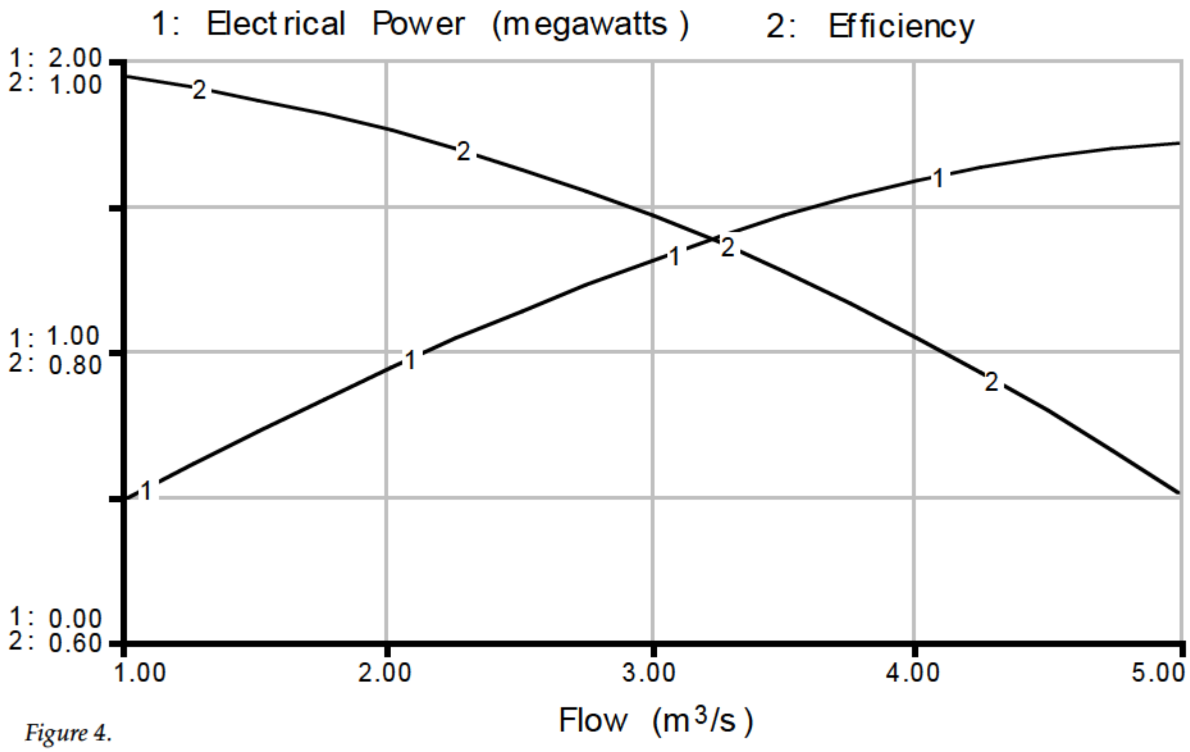


Figure 4.

operate unless the water leaves the turbine fast enough to allow new water to enter it. An automobile will not run if the hot exhaust gases are not forced out and fresh air sucked in. Your automobile engine spends three-fourths of its time moving gases around and only one-fourth of its time producing power. A furnace will not work unless we allow hot gases to come out of the flue, taking with them some of the energy.

Thermal Systems

If two objects at exactly the same temperature are brought into contact, no heat or thermal energy will flow between them. If one object has a higher temperature, T_1, than a second object, T_0, thermal energy will flow from the warmer object to the cooler object when the two are brought into contact. This process is *thermal conduction*; the equation describing the process is very simple:

$$P_C = K\,(T_1 - T_0)/D \qquad (11)$$

where D is the distance between T_1 and T_0, K is a constant called the thermal conductivity of the material between T_1 and T_0, and P_C is the power per unit area flowing between the two points due to thermal conduction. Different materials can have widely varying values for K, as we see in Table 3.

The materials listed in the table are building materials (except water and air, which are listed for comparison). The values in the second column represent the power conducted through 1 square meter of the material that is 1 cm thick when the temperature drop across the 1 cm is 1 °C. For example, a 1-cm thickness of gypsum board will conduct 40 watts/m^2 when there is a temperature drop of 1 °C across the gypsum board.

A more important example concerns a 2-mm thickness of windowpane glass with a 1-m area. When the temperature drop across the glass is 20 °C (or 36 °F, 32 °F outside and 68 °F inside), the heat loss is 8,000 watts per window; this corresponds to 80 light bulbs at 100 watts each for every window in the house. Most people would never deliberately turn on that many lights and waste that much energy, but those same people do not replace their windows or

Material	Power Conducted W/m²	Equivalent Thickness
Aluminum	20,000	5,000
Concrete	100	25
Glass	80	20
Brick	60	15
Water	60	15
Gypsum	40	10
Cinder block	30	8
Wood (variable)	10	2.5
Fiber glass	4	1
Air (nonconvective)	2.5	0.6

Table 3

otherwise minimize the heat losses from their homes or businesses.

The third column compares the heat-stopping power or insulating capability of the various materials compared to one unit thickness of fiberglass insulation. For example, we see from the table that a brick wall 15 inches thick has the equivalent insulating properties of 1-inch-thick fiberglass. We would require 5,000 inches of aluminum to insulate as well. Materials that are good electrical conductors are also good heat conductors, because of all of the loose electrons capable of moving around in the material.

If we heat a parcel of a fluid that is surrounded by a cooler parcel of the same fluid, the warmer fluid expands and becomes less dense. The more dense adjacent fluid will move underneath the less dense parcel and displace it upward. (Hot air rises because the cooler air pushes it upward.) The combined motion of warmer fluid moving upward and cooler fluid moving downward produces an upward flow of thermal energy that we call *convection.*

Convection is a process that involves complex turbulent motions in the fluid and cannot easily be described mathematically. We do know that convection is much more efficient than conduction in fluids; therefore convection is always present in fluids when differential heating or cooling occurs. The convection processes, rather than conduction, transfer thermal energy in fluids except at boundaries with solids, where once again conduction dominates. The purpose of fibrous insulation materials, such as fiberglass and cellulose, used above ceilings and in walls, is to prevent convection from occurring. These insulating materials produce so much friction on the motion of the air that convection cannot occur.

Advection is a process similar to convection, in which the fluid is forced to move by winds, pumps, or fans, predominantly in the horizontal. When you stir a pot of soup, turn on a ceiling fan, or open a window to let the breeze in, it is advection that is moving the thermal energy.

Thermal energy can also be transferred by radiation processes; *thermal radiation*, P_T, is a sensitive function of temperature, T,

$$P_T = \sigma T^4 \qquad (12)$$

where the Stefan-Boltzmann constant, s, is

$$\sigma = 5.67 \times 10^{-8}\ \mathrm{W/m^2/K^4} \qquad (13)$$

P_T is radiated power in watts per square meter, and the temperature must be expressed in Kelvins or absolute temperature. Thermal radiation is another form of electromagnetic radiation that we discussed earlier. Equation 12 goes by the strange name of "the blackbody radiation law"; most solid and liquid surfaces at normal temperatures will produce thermal radiation according to this law. Blackbody radiation occurs when the atoms and molecules in a substance are closely packed so that they are continuously interacting and some electrons are loosely shared. When the atoms and molecules are widely separated and independent, as in a gas, they cannot collectively radiate as a blackbody but can only exchange radiation at specific wavelengths determined by changes in the energy levels of their atomic and molecular structure.

The energy-level changes in the diatomic molecules, nitrogen and oxygen, that make up 99% of our atmosphere are too large to absorb or emit radiation in the visible or infrared regions of the electromagnetic spectrum; because of this our atmosphere is mostly transparent to solar radiation. On the other hand, the triatomic and larger molecules, water, carbon dioxide, methane, ozone, etc., have lower energy-level changes that allow them to absorb and emit electromagnetic radiation in the visible and infrared; these are the "greenhouse" gases. Without the greenhouse gases earth would be a frozen wasteland; too much and earth may become too warm.

It is not chance that we see in the visible part of the spectrum; it was an evolutionary necessity that our vision work in the transparent part of the atmosphere.

Another important characteristic of black-body radiation is that the temperature of the radiating material determines where in the electromagnetic spectrum most of the energy is radiated. This peak in the radiation spectrum occurs at the wavelength, λ (in µm), given by Wien's Law

$$\lambda = 2898/T \qquad (14)$$

where T must be in Kelvin or absolute. This equation tells us that the hotter the material the shorter the wavelength of the peak power. Table 4 will give you a feeling for the range of thermal radiation that we normally encounter.

The wavelength range for visible light goes from red at 0.7 µm to violet at 0.4 µm, which is not very wide. Of the thermal radiating objects in the table, only the sun has a peak in the visible range. The incandescent or tungsten light bulb (at 3,200 K) produces a yellowish-white light, and color photographs using this light do not reproduce true colors. Even though it appears nearly white, most of the power used by the light bulb is going into infrared radiation and heat. Only 2% to 5% of the electrical energy used by the light bulb produces visible light—light bulbs are notoriously inefficient. All systems that depend upon thermal radiation to produce visible light will be inefficient, because visible light is a narrow spectral range and thermal radiation is very broad. Fluorescent lights can achieve efficiencies in the 10% to 12% range, which is not very good but far better than the incandescent light bulb. Fluorescent lights do not use thermal radiation; they have a chemical coating on the inside of the tube that "fluoresces" when excited by the plasma discharge in the gas inside the tube. To explore how different lights work, go to http://www.sylvania.com/cool/welcome.htm on the World Wide Web.

The flame temperatures for methane (natural gas) and gasoline are shown in the Table 4. Clean-burning flames do not produce black-body radiation because they are gases. The yellow flames that we see in wood fires and candles are hot particles of incomplete combustion products. When you extinguish a candle you will see these particles rising above the candle as smoke.

In many situations, all four of the thermal transfer processes (conduction, convection, advection, and radiation) will be working simultaneously. Your room may have a forced air heating and cooling system that moves air into and out of the room by advection. The walls, floor, and ceiling are radiating thermal energy trying to keep everything at the same temperature. At the window, heat is being conducted through the glass, and at both glass surfaces heat is conducted to or from the adjacent air. The air adjacent to the glass will sink if cooled or rise if warmed; in both cases convection is moving the thermal energy around. There are so many processes that transfer thermal energy that it is no wonder that thermal systems tend to be inefficient. The good news is that we know how to deal with these inefficiencies, and if motivated we can achieve great energy savings.

Our heat conduction equation (11) displays fundamental and important behavioral information about thermal systems; the heat you move is proportional to the temperature

Table 4

Radiating Object	T (K)	Peak (μm)	Appearance and Comments
The earth on average	288	10.1	We see reflected light, not thermal radiation; effective temperature whole earth ~15 °C
A wall in your room	295	9.8	We see reflected light not thermal radiation; ~72 °F
Electric heater, range on high	960	3	Dark red glow, also wood fire, 650–750 °C; aluminum alloys melt
Toaster element	1,160	2.5	Bright red glow, also coal fire, 850–950 °C; brass and bronze melt
Forge, forced-air coal	1,360	2.1	Yellowish red, 1,050–1,150 °C; copper and iron alloys melt
Molten steel	1,760	1.6	White heat, 1,450–1,550 °C; steel melts ~1,370 °C
Maximum methane flame	2,140	1.4	Colorless (blue emission is not blackbody but excited gas molecules), 1,870 °C
Maximum gasoline flame	2,500	1.2	Colorless; camping lantern makes white light, gas flame heats the ash mantle, ~2,000 °C
A light bulb, tungsten filament	3,200	0.9	White; tungsten melts at 3,655 K; design compromises temperature with bulb life
The sun, photosphere	5,770	0.5	White by definition; the photosphere is the visible layer of the sun, 5,500 °C
A lightning channel	30,000	0.1	White; the duration of the optical flash is only tens of μs

difference. The final process of transferring heat energy involves transfer to the environment at T_E. There is another relationship for the efficiency of a heat engine that is equally important, the Carnot Cycle.

If we were to imagine an absolutely perfect engine that converted heat energy at T_H to mechanical energy, we would find that the efficiency of the engine would be given by the Carnot equation:

$$E = (T_H - T_E) / T_H \qquad (15)$$

We see once again that it is the difference in temperature, in this case between the source and the environment, that limits performance.

For an example, let's start with a simple steam engine (T_H = 373 K = 100 °C) in an environment of T_E = 303 K = 30 °C (= 86 °F). The efficiency of the perfect engine operating at these temperatures is

$$E = (373 - 303) / 373 = 19\%$$

Real steam engines increase efficiency by using steam under high pressure, which has a higher temperature, but in practice they are also faced with higher exit or environmental temperatures.

To appreciate the difference between the exit temperature and the environmental temperature we can split the steam engine into two parts. The first part transforms the heat energy into mechanical energy, and the second part moves the waste heat from the engine into the environment; this latter part is the required waste power discussed in the previous section, and the engine will not run if the second part of the engine cannot perform this essential function. If the steam engine is approximately 20% efficient, then the second part, the cooling part of the engine, must handle 80% of the input energy. There are three temperatures that must be considered: T_H, T_E, and T_e, the exit temperature of the first part of the engine and the input temperature to the cooling part of the engine. In order to move large quantities of waste power through the cooling section, T_e must be greater than T_E, but increasing T_e necessarily decreases the efficiency of the first part of the engine, which is the part that produces the mechanical power of the engine.

The best efficiency ever produced by classical (reciprocating) steam engines was 25%, but this was with large and heavy engines because the steam pressure had to be increased by 100 times to achieve this efficiency. The classical steam engine has been replaced by steam turbine engines that are much lighter. A steam turbine with an input temperature of 600 °C can operate with an efficiency of approximately 40%.

Energy Quality

In this section we want to introduce you to an important concept that describes the quality of energy. A 12-volt automotive battery, fully charged, can store roughly 3×10^6 J of energy. By comparison, a lecture hall (6 m × 8 m × 4 m) in which the air temperature has been warmed by 10 °C relative to the environment has the same amount of energy.

The automotive battery may be used to

1. produce mechanical energy in a starter, winch, fan, or other electrical motor;
2. produce light when connected to an automotive lamp;
3. produce and receive electromagnetic radiation when connected to a radio transmitter or receiver or cellular telephone;
4. produce acoustic power (sometimes too much) when connected to an amplifier and loudspeakers; and
5. heat the lecture hall by 10 °C, when connected to a heater.

Now, what kind of energy transformations are available to the warm room? Only one: when you open the door, a convective current will be produced that allows the cooler outside air to enter the lower level of the room and pushes the warmer air out the door. You can never charge the battery using the warm air.

Although the *quantity* of the energy is the same in these two examples, the form or *quality* of the energy is very different. It is this difference in quality that we wish to explore.

We find the explanation for the quality of energy in the science of thermodynamics, which literally means heat energy dynamics. The First Law of Thermodynamics says that energy is conserved in a closed system. We have used this law many times in this book already: you can transform energy or move it, but you cannot create it or destroy it. The Second Law of Thermodynamics is just as important but more subtle because it involves an understanding of entropy, which we will now explore.

Entropy measures how broadly the energy in a system is distributed—in other words, how much disorder there is in the system. In our previous example the warm room distributed its energy among all of the molecules of gas in the room; the system was highly disordered. The battery, however, had all of its energy highly concentrated in the chemical compounds attached to its plates; the system was highly ordered. Even though the energy is the same, the warm room has higher entropy than the battery. The quality of the energy in the battery is much higher from the human perspective because it is easily transformed into useful forms; we therefore associate high quality with low entropy.

The Second Law of Thermodynamics says that entropy is always increasing in closed systems. That's a bummer! The first law says that we can never get any new energy, and the second law says that the energy that we have is continuously getting less useful. Physicists sometimes refer to this process as the heat death of the universe. These two laws should make us all more conscientious users of energy even if there were no energy crisis.

We have already seen several consequences of the second law. The law of thermal conduction given in Equation 11 says that energy only flows from the warmer object to the cooler object, and furthermore, that the rate of energy flow is proportional to the temperature difference. This is a consequence of the second law, because the heat transfer process distributes the energy more broadly: entropy increases. The Carnot equation (15) is very similar; you cannot create an efficient engine with small temperature differences—or, stated differently, if you design your engine to work with nature, it will be more efficient.

For thermal systems there is a rather simple expression for the change in entropy, dS, that occurs in a system when a quantity of thermal energy, dQ, is added to the system:

$$dS = dQ/T \qquad (16)$$

where T is the temperature associated with the energy being transformed. This entropy equation demonstrates the close connection that entropy has to temperature; for the same quantity of energy (dQ) the entropy is smaller for higher temperature. Since energy quality is associated with low entropy, we can associate high temperature with high quality with respect to energy transformations. (This is only a small part of the story of entropy. We have left out many other important considerations, such as phase transformations, but the simple result used here is very powerful.)

We can extend the concepts of these laws of thermodynamics to include other forms of energy. In the case of electromagnetic energy we can use Wien's Law (14) to relate the wavelength of electromagnetic radiation to a temperature. See the examples in Table 5.

For electrical energy we convert the energy gained by an electron accelerated in a vacuum through one volt and use an equation like Equation 7 to associate a temperature with a volt. We find that one volt is roughly equivalent to 10,000 K; the energy gained by the electron is equivalent to a molecule of gas heated to 10,000 K. Recall that the electrical force is a strong force, and also recognize that a small flashlight at 1.5 volts can produce nearly white light by the very inefficient process of incandescent light. The electrical examples in Table 5 all have high associated temperatures.

In Table 5 the "Quality Temperature" is a scale based on energy comparison that is useful in applying thermodynamic concepts across the broad range of human energy use. Our earlier example of the car battery and the warm lecture room can now be viewed with a quality temperature approach. The car battery has a quality temperature of 120,000 K, while the room temperature is only 300 K (~86 °F). It is easy to see how the battery can produce light at 3,200 K and follow the Second Law of Thermodynamics, which requires energy to flow from the higher to the lower temperature, but the warm room cannot produce light (or any of the other manifestations listed) because its temperature is only 300 K.

Equation 15 gives the efficiency for the perfect engine, which we have seen for steam turbines is less than 45%. Electric motors can be produced to operate close to 100% efficiency because the input or quality temperature is over 100,000 K.

Table 5

Energy Type	Quality Temperature (K)
Visible light (0.5 μm)	5,800, the surface temperature of the sun
Earth infrared (10 μm)	288, the average earth temperature
Solar ultraviolet (0.25 μm)	10,000, the source of sunburn
Gamma rays produced in nuclear disintegrations	50 billion represents the very strong nuclear force
Flashlight with two batteries (3V)	30,000 represents the strong electrical force
Household electricity (120 V)	1.2 million; small wires can be explosively vaporized with household electricity
Gasoline burning in air	2,500, the maximum

What Do We Do?

Automobiles

A major culprit in the energy/fuel crisis is, undeniably, the automobile, and the number one abuser of automobile use is the United States. Roughly a third of all of the world's automobiles are in the United States, which has less than 5% of the world's population. Our gasoline consumption for cars and trucks alone is sufficient to supply the entire energy needs of Japan. Our cars are larger and less fuel efficient than those in the rest of the world. The bad news is that we are gasoline pigs; the good news is that we have lots of room for improvement in our behavior. The automobile fuel problem is not just a U.S. problem, because automobile use is rapidly growing all over the world. There are now as many cars in Europe as in the U.S.; however, since there are twice as many Europeans, we have twice the number of cars per capita. The world's consumption of gasoline for cars uses half of the total oil production on the planet. So, what do we do?

There are many aspects to the automobile problem, ranging from ego to thermodynamics. We will consider the simple one first—thermodynamics. We have all heard the conspiracy rumor that there exists a carburetor that will permit cars to get 100 miles to a gallon of gas, but the auto and oil giants keep the carburetor off the market. This rumor is not true; there are real engineering and scientific limits to the efficiency of internal combustion engines. We see in Table 4 (p. 21) that the combustion temperature of gasoline is 2,500 K; we also see in the table that steel melts around 1,600 K and other metals at even lower temperatures. Does this mean that we can't use gasoline in metal engines? Obviously we can and do. It means, however, that we must cool the combustion chamber down below ~800 K to prevent the engine from seizing up when the metal parts expand from the heat. What a waste! By having to cool the engine, we lower the "quality temperature" of the energy from 2,500 K to below 800 K. This is where the cooling system in the car comes into play. Liquid coolant is circulated through the engine, where it picks up heat; it is then pumped to the radiator, where it releases this energy into the atmosphere. Right off the top, one-third of the total available energy in the gasoline is lost in keeping the engine cool enough to run. Another bad result of cooling the combustion process is that it does not allow the chemical reactions to complete. Without the cooling there would be few "incomplete combustion products" and hydrocarbons in the exhaust to produce automotive pollution and smog, because complete combustion produces only carbon dioxide and water. In other words, automobile pollution is a result of the necessity of keeping the engine cool. The function of the catalytic converters is to provide a hot environment for the incomplete combustion products to complete their reactions. The catalytic converter gets very hot because it is burning combustion products not used in the engine. Waste power.

Next the engine must push out the combustion products and suck in fresh air and gasoline for the next power stroke. This process forces out very hot exhaust that carries one-third of the gasoline's energy into the air as hot, smelly, exhaust fumes. This is also part of the "required waste power." There has got to be a better way! Most of us don't think about the consequences of having a 100 horsepower engine; it demands a 100 horsepower cooling system, a 100 horsepower exhaust system, and a 200 horsepower braking system.

At this point in our analysis we are down to approximately 33% efficiency, and we have not considered friction. When friction and stop-and-go traffic are considered, the efficiency drops to 20%. Then adding energy use for automatic transmissions, air conditioners, lights, fans, radios, etc., we find that in real use the average efficiency is around 10%. Only 10% of the energy available in the gasoline is used in moving the car.

Now that we have the automobile moving, let us explore the question of the appropriate use of the automobile. The most common use of a 5,000-pound automobile is to move a 160-pound driver from point A to point B and back. Only 3% of the energy going into motion is actually moving the driver. If we take into account all of these factors involved in using a gasoline-powered automobile to move the driver, we see that the trip is only 0.3% efficient.

What do we do? Reduce the number of trips in the automobile. Bike. Walk. Combine your errands into fewer trips. Substitute a telephone call for a trip.

Another response to the question above is to reduce the weight of the automobile. The ideal arrangement would be for every family to have an array of transportation means from which they could select the most appropriate one for each use: a small one-person electric "car" to make short trips to the grocery store; an electric two-seater for short commutes to work, or a lightweight two-seater gasoline car for longer commutes; an electric four-seater for taking the kids to school and other short carpooling duties; and a gasoline-powered family car for long trips and vacations. Even if this array of vehicles were available on the market, it is the rare family that could afford to own them all. What we typically do is purchase the vehicle that meets our most demanding need; we end up with the heavy family car, which is used for all of the other inappropriate functions. *What do we do?* Rent it. If you only *really* need the big car three or four times a year for visiting grandmother or taking the family vacation, you will save a lot of money by renting the big car only when you need it rather than buying it, maintaining it, and paying insurance all year long.

Imagine an anthropologist in the year 3001 giving a slide lecture on civilization and cultural change. "The Twentieth Century is known as the automobile culture; in the wealthy nations every person had their own private, gasoline-powered, metal automobile large enough to seat six adults and powerful enough to travel 40 m/s." (This is ~90 miles per hour; Congress finally approved the metric system.) There are surprised gasps of disbelief from the students as the lecturer shows them slides of people in their large, powerful cars; crowded freeways; parking garages; and motor homes. A student asks, "What happened to the automobiles; why did they stop using them?" She replies, "They ran out of fuel. In a brief 200-year period they had consumed all of the petroleum." More gasps from the students, and another question, "Do you mean that in a 200-year period they used up all of the petroleum on this whole planet? Didn't they know what they were doing?" She replies, "They knew, but they could not stop themselves. Some scientists now think that they were addicted to using the automobile. We don't know whether there was something in the fumes that caused the addiction, or whether there was a psychological addiction to the control of power, but they just kept on driving until the fuel ran out. By the way, it was the burning of the fuels that caused the great global warming during the last millennium. You should take a submarine tour of some of the ruins of their large coastal cities sometime."

The automobile *is* our defining cultural influence. The signature of the automobile is written all over the human landscape. All of the modern cities (those built or grown substantially since the introduction of the automobile) are designed for automobiles. Look critically at a map of a large city; the organization of everything that you see—the freeways, the bridges, the width of the streets, the location of buildings, parking—has being dictated by the automobile. Pedestrians and bikers are dead meat in a city like Houston, Texas. Suburbs are an artifact of automobiles. Shopping malls with their giant parking lots are creations of the automobile. The great architectural monuments of Ancient Egypt are the pyramids, of the Chinese Empire it is the Great Wall; our culture will be represented by our freeways. Actually, some urban freeway interchanges are architecturally beautiful—four to six levels of gracefully arching roadways that rise above the surface and above many of the nearby buildings. We are the automobile culture.

Consider also the far-ranging influence that the automobile has on the economy: the steel, aluminum, glass, and plastic used in manufacturing; the battery lead, tire rubber, and coolant chemicals needed for operating the automobile fleet; and the gas and oil continuously required to run them. How large is the fraction of basic materials flowing in the stream of extraction, refining, and production that is related to automobiles—not just the amount used in the manufacturing of the cars, but also the materials used to build highways, bridges, parking facilities, service facilities, etc.? What fraction is involved in keeping the oil and gas flowing? There is the petroleum exploration industry, the petroleum production industry, the fleets of tankers and miles of pipelines, the refineries, the jobbers and haulers that distribute the products, and finally the stations that pump the gasoline into your car. How many jobs are there in this chain; how large is this economic component? And in the public sector, how many state, county, and city employees have automobile-related jobs—police, road maintenance, lights and signals, license, registration, inspection? What fraction of the economy is involved in the actual selling of new and used cars and in handling junk cars? Taken all together, from the gravel pit operator to the automotive engineer, the automobile is a huge component of the global economy. Oil alone is a dominant factor in global economy and politics; recall the recent Gulf War and ask if the United States would go to war today over anything else besides oil.

What do we do? Apply economic forces to persuade us to use the automobile more sensibly; this means increasing the taxes on gasoline. We do not pay actual costs for using the automobile. The fuel is priced far below its true value. We use property and sales tax income to subsidize the infrastructure costs associated with automobile use. We should start increasing the tax on road fuels by 10% a year; after 10 years we would be paying approximately what Europeans pay for gas today. The steadily increasing cost of gasoline would, it is hoped, persuade us to decrease our use of the car, use alternate transportation, and buy a more fuel-efficient car at the next purchase. The new tax income should be devoted to research, development, and demonstration of alternate transportation means and fuels—everything from electric bicycles to fuel cells.

What else do we do? We become aggressive advocates of fuel taxes, public transportation, new transportation technologies, and research and development of new and more efficient fuel systems for transportation. In the present political environment, no politician who wants to be reelected will come forward and advocate increasing gasoline taxes, because the whole electorate drives cars and many are employed in the automobile infrastructure. These voters must be convinced that in the long run we all benefit by reducing automotive fuel usage.

Buildings

If we divide the total energy-use pie into three slices—transportation, industry, and buildings—we find that the two largest slices are industry and buildings, each representing ~38% of the energy-use pie. Transportation is the remaining slice at ~24%. There are several reasons that we have focused so much attention on the transportation sector in this book. First, the transportation sector is totally dependent upon oil for its fuel, and oil is the fuel in shortest supply. The industry and buildings sectors use a broad mix of energy sources: coal, oil, natural gas, hydroelectric, nuclear, and other; these energy resources are in greater supply than oil. Second, the technology for replacing the gasoline-powered automobile is not immediately “at hand”; we cannot go to the hardware store and purchase something to improve the efficiency of the automobile, which is possible for buildings. Third, the transportation sector is rapidly growing in global energy consumption, whereas the two other sectors are actually declining because of improving efficiency.

The industry sector has a built-in motivation to continuously improve its energy efficiency: competition. The cost of energy becomes part of the cost of the product. If your competitors can produce the same product with less energy, then they can sell the product at a lower cost, undercut your price, and capture your market. As the cost of energy slowly rises to reflect its true value, then the motivation for industry to work harder in improving efficiency will be increased. *What do we do?* A simple ramping up of the cost of energy is sufficient to keep the energy efficiency continuously improving in the industry sector of the energy pie.

In this section we are focusing upon buildings, and we are including residential and commercial buildings together, because they share many of the same waste energy problems and energy conservation solutions. The good news is that the technology and knowledge to achieve large improvements in building energy efficiency are readily available. You can literally purchase energy-saving devices and materials off the shelf at your local hardware and building material store.

The energy uses in buildings fall into the following basic categories:

1. heating or cooling of the interior relative to the exterior environment and distribution of conditioned air within the building;
2. large appliances such as dryers and ranges in homes and copy machines in offices (these usually require 220 V power connections);
3. lighting;
4. water heating; and
5. small appliances such as computers, stereos, and TVs.

This list is roughly in the order of decreasing energy demand, but the order will change slightly with your local climate and function of the building.

Usually, the largest energy demand will be for heating (in Minneapolis) or cooling (in Houston), but the problems are very similar—reducing the thermal energy exchange. The solution is thermal insulation. Energy is transferred through ceilings, walls, and floors, but the greatest losses are in windows and doors.

Heating and Cooling

There are simple solutions for these energy transfer problems. In the “Heat or Thermal Energy” section we computed the energy loss by conduction through a single glass pane; it was very large. There are many excellent alternatives to the single pane today. Double glass panes are readily available for all windows and glass doors. On special order you can get triple glass and other superinsulated glass windows. The superiority of these multiple-layer designs is not simply that the glass is thicker but that there is air (or in the most advanced designs argon) sandwiched in between the panes of glass. Look at Table 3 (p. 19) and the associated example. A 2-mm-thick pane of glass under the specified conditions in the example conducted 8,000 watts of heat through the glass. If we simply increased the thickness of the glass to 4 mm, we would reduce the energy conducted by a factor of two (4,000 W). A significant improvement occurs when we sandwich 2 mm of air between the two 2-mm panes of glass. The conductivity of air is so much smaller than that of glass (see Table 3) that the energy loss is reduced to

~250 watts, a significant improvement. In these designs making the air space wider will not improve insulation, because a wide air space promotes convection, and heat transfer by convection between the two panes would be greater than by conduction. The window design must be narrow in order to prevent the air from circulating inside the space.

For new construction investing in good double-pane windows is the wise decision, and it will eventually pay for itself. For older construction the windows can be replaced with double-pane windows, but if this seems too costly for the older house, storm windows can be installed on the outside to provide a trapped air space between the windows.

If your building is in a severe climate, you should consider triple-pane or equivalent windows. This will require an increased initial investment, but the energy savings will eventually pay for the difference in investment.

Insulation for ceilings and walls is extremely important and relatively inexpensive. Adding insulation inside exterior walls of older buildings may be problematic; it may be necessary to remove some of the sheetrock in order to fill the space behind it. It is sometimes possible to drill small holes (~1 inch) near the ceiling line between each stud and fill the wall space by injecting the insulation through the hole, which is then plugged. Ceiling insulation can be added or increased at any time; loose insulation can be blown onto the ceiling from the attic by commercial contractors, or if there is sufficient working space in the attic, the owner can lay down insulation "bats" between the rafters or pour in insulation from bags.

It is very important to stop all air leaks around doors and windows. Check them annually and replace the weather seals when needed.

Floor insulation decisions depend upon the construction. In buildings with the bottom floors elevated above the surface on piers, there are two insulating strategies to be followed. First, the perimeter of the base of the building should be sealed to create a dead-air space under the floor and prevent advection losses. Second, insulation "bats" should be installed between the floor joists. This is a bit more difficult than installing them in the attic, because the bats must be stapled to the joists to hold them in place underneath the floor.

Most recently constructed buildings have concrete slabs for the bottom floor. These floors are thermally connected by conduction to the ground underneath and tend to maintain a nearly constant temperature. If the average soil temperature in your environment is cooler or warmer than the temperature of your building, you will be using building energy to warm or cool the soil underneath the foundation. Adding a wood floor or thick carpet with a thick carpet pad will help insulate the building from the slab. If you are involved in designing the building, you can place the slab below grade level (the ground surface) to reduce the seasonal variations in soil temperature, and thick construction insulation can be installed between the foundation wall and the outside soil; this will help isolate the foundation from the outside soil.

Having created a well-insulated building, we next consider the technologies for heating and cooling. For cooling there are limited choices; you must go with a forced air circulation system in which the air in the building is circulated and advected across coils that are cooled by refrigeration (a.k.a. a central AC system). Electric motors are very efficient, so the air circulation part of the cooling system is not a major energy problem; additionally, the same air handling system can be used during the periods that require heating. Another plus is that the air is filtered as it passes through the system. It is the refrigeration part of the system that uses most of the energy, and for that there are two choices: electric or gas. Gas units are not available for small applications, so most homes must use electrical air conditioning units. If you have a ready source of natural gas to your building, the gas unit may prove more economical to operate. If your building is in the hot, humid South, count on cooling to be the largest operating cost in maintaining your building.

There are a lot more options to be considered for heating a building: coal, oil, propane, gas, electricity, wood, and solar. Within each of these energy sources there are many technologies available. Coal and wood are only ~50% efficient; they are not practical unless your building is located near a forest or coal mine. They also emit pollution and are inappropriate for an urban environment. Oil furnaces are efficient in the 55–65% range and have similar pollution emissions to those of coal, but in smaller amounts. Propane and natural gas are almost interchangeable; simple conversions can be made on heaters to accommodate either fuel. An ordinary gas burner in a central AC system burns clean with an efficiency of ~70%. This efficiency is limited by using the hot combustion products to create an updraft in the flue and pull fresh air into the burner; this is the required waste power of the natural gas draft burner system. There are forced-flow, condensing, gas systems that operate with 95% efficiency. These systems do not depend upon the hot combustion products to provide draft. Much more of the available energy can be extracted to heat the building. In fact, in these systems, the water vapor produced in the combustion actually condenses to liquid water and adds its latent heat energy to the building heating. Natural gas is our cleanest burning fuel and the supply is good. This combination of a clean, plentiful fuel and a technology that is 95% efficient make this the preferred means of heating buildings.

Electricity is frequently used for heating. Electricity is a necessary utility in all buildings. Many builders will elect not to install gas to keep the construction costs lower. Thus, we end up with all-electric homes and all-electric apartments. Electricity is not a wise choice for heating when there are other, better options. The electric utility has used a fuel, such as natural gas, to generate electricity at an efficiency of ~40%; you can burn that same fuel for heat at twice the efficiency of the power plant. The cost differential is also great, because the electric utility adds its operating costs and profits on top of the fuel cost. Electricity is clean and most convenient, but it is an expensive way to heat.

There is another way to heat with electricity that is much more efficient. This is the heat pump. The heat pump is a refrigeration cooling system operating backwards. It removes heat from the outside air and pumps it inside the building. A heat pump unit can serve as a cooling system in the summer and a heating system in the winter. It does not operate very efficiently when the outside air is really cold.

We have discussed the central AC system for distributing heating and cooling throughout the building. This is the most widely used system in modern buildings. There are other technologies for distributing heat. Steam heat, which employs a central boiler and distributes steam through pipes, was widely used in buildings in the past but less in modern buildings; it is efficient but difficult to maintain. Hot water systems are similar to steam but are less efficient. These are found primarily in dwellings; the hot water may be circulated through baseboard heaters or the pipes may be routed in the floors to heat the floors. Gas space heaters are rarely used any more because they can produce carbon monoxide gas in closed spaces. Electric heat may be delivered by baseboard heaters or at high temperatures in radiating space heaters. Electric heating may also be incorporated in a central AC system. There are lots of options; be informed and choose wisely.

Large Appliances

There are two aspects of energy usage that should be considered in the large appliances, energy consumption and released heat load. The first is straightforward: how much energy does the appliance require? The second is more complicated: how does the heat released into the building impact the heating and cooling system of the building? In some large office buildings the heat produced by the lights, computers, etc., is so large that the cooling system must operate all year long. When selecting a large appliance, explore these two questions and select the most energy conservative option.

All large appliances produce waste heat. In the home the kitchen is a "hot spot." The heat producers are refrigerators, ovens, stovetops, dishwashers, and microwave ovens. To control this heat you will need good venting and good air circulation. If your house is in the heating mode (wintertime), the released heat can be circulated through the house and reduce the energy needs of the primary heating system. If you are in a cooling mode (summertime), the released heat should be vented outside to prevent overloading the primary cooling system. Similar considerations should be given to other areas in the house where large appliances are located: washers and dryers, water heaters, and bathrooms, where large quantities of hot water is used.

In commercial buildings (factories are included in the industry sector), typical large appliances are photocopy machines and mainframe computers, and in retail buildings they are refrigerators and freezers in grocery stores. In office buildings these large appliances should be isolated in special areas where venting and air circulation can be controlled. Retail stores face difficult choices, because effective displaying of the merchandise runs counter to efficient energy use in many situations. A prime example is the vertical freezer cabinet for displaying prepared frozen foods in grocery stores. The freezers are well lit, which has a double energy cost, with energy needed both for the lights themselves and for removing the heat that they produce in the freezer. Even worse, when the door is opened to remove a product or even read a label, all of the cold air rushes out (you can feel it around your feet) and is replaced by building air. The freezer must then cool this warmer air. Roughly one-fourth of the floor space in a grocery store may be dedicated to refrigerators and freezers; if these are self-contained units (each with its own cooling system), they are discharging a very large heat load into the building, which in a cooling mode must be removed by the primary building cooling system. Refrigeration requires a lot of electrical energy, and the compound cooling problem of the grocery store is an expensive and energy-inefficient operation.

What do we do? (1) When purchasing a large appliance, research the energy use and select the most energy efficient appliance that performs the required function. Also research alternate technologies; you may find a better way to accomplish your task. For example, instead of purchasing a large side-by-side refrigerator-freezer combination for the kitchen in order to freeze your annual venison acquisition, consider a smaller refrigerator with overhead freezer for the kitchen and a small chest-type freezer for the laundry room, garage, or basement. When you open the freezer door of the big unit, all of the chilled air escapes and is replaced by warm, moist room air. This air is chilled and the moisture condenses on the cooling coils, which after a few days must be defrosted. Every time you open the freezer for an ice cube, a whole sequence of energy-consuming processes is initiated.

The large side-by-side refrigerator-freezer combination unit has a compressor, a condenser fan, a freezer fan, a refrigerator fan, a defroster heater, and door heaters to keep the door gaskets pliable. In contrast, the smaller refrigerator unit uses natural convection to replace the condenser fan, uses gravity and convection to replace the freezer and refrigerator fans, and has no door heaters. The smaller unit has a defrosting heater, but it is needed much less frequently because the air exchange is significantly smaller every time the freezer door is opened. Both units may have ice makers, which is an even tradeoff. The chest-type freezer is the most efficient of all freezers; it can use a small compressor and has no fans. When you open the lid/door to select a package of venison sausage, the cold heavy air stays in place; there is almost no air exchange with the room. Choosing the option of two small units rather than the big combination unit yields a great energy savings, and probably lowers repair costs since there are fewer motors to replace.

(2) When you consider the purchase of a large appliance, plan ahead for where it will be placed and how it will impact the energy distribution of the building. Explore ways to minimize the adverse impacts of the waste heat released.

(3) Do you really need that large appliance? How often will you use its special capabilities? Can you get by with a smaller copy machine in your office for most jobs, and send the larger jobs out?

Lighting

Here are some simple ways to save energy on lights.

- Use natural lighting to the maximum. Everyone prefers an office with a window; it is partly to be able to look out, but mostly people prefer natural lighting. Expert architectural design can make use of natural light while carefully managing the heat load from direct sunlight.
- Use light-colored (as in white) interior paint to promote uniform illumination.
- Do not use the general room lighting to provide light for special work areas.
- Use directed, appropriate lighting for work areas. Computers are becoming commonplace on office desks. A brightly lit computer is not good, but it is good to have a brightly lit desk space adjacent to the computer. General room lighting cannot accomplish this.
- Use the higher-efficiency fluorescent and halogen light bulbs. Ordinary tungsten bulbs are ~2.5% efficient; 100 W of electricity produces 2.5 W of light and 97.5 W of heat. Halogen bulbs produce 10% more light, which is whiter and closer to natural, and they last three times longer. Fluorescent bulbs are five times more efficient than tungsten and last 25 times longer. Fluorescent bulbs should be used for all general lighting applications; halogen bulbs should be used for work areas because they are easier on the eyes.

What else do we do about lights? Turn them off when they are not being used or when not needed. Without question, the greatest potential energy savings for lighting is in learning to turn the lights off when you exit an empty room. Another bad habit is turning the lights on when they are not needed, when there is ample natural light available.

Lighting for retail sales presents a challenge. Customers expect to see goods displayed in bright, uniform lighting. I recall recently visiting a major national chain store that had rather old fixtures and lighting; everything looked like used goods. The energy-wise decision for retail sales lighting has to be to install the most energy-efficient fluorescent fixtures available and to feature samples of the products at highly illuminated special display areas that are spaced at intervals throughout the store.

Water Heating

Water heaters are major energy users in homes and in office buildings to a lesser extent. The energy source choice here is gas or electricity, and the delivery system choices are central tank, central tankless, distributed tanks, and distributed tankless. Gas is preferred to electricity because of the energy loss in producing electricity and the costs of the electric utility added to the fuel cost. Tankless is preferable to tanks, because the water in the tank must be kept hot all of the time, whether you are using it or not. A tankless water heater is off until someone turns on a hot water valve; it comes on immediately and heats the water as it flows through a network of pipes in the heater. It has the advantages of heating only on demand, and it can supply hot water continuously—you never run out of hot water. If you are using gas, central water heaters are more practical because they avoid the complexity of plumbing the gas and exhaust flues into the kitchen, bathrooms, and laundry. The disadvantages of the central unit are that you sometimes have to wait for the hot water to travel from the heater to the faucet, and when you turn off the faucet, there is a pipe full of hot water that may cool off and be wasted. If you will be using electrical water heating, consider the distributed water heating system. This type of system has small electric water heaters in every place that the water is used; thus, the hot water is quickly available. This would be an appropriate technology to use in an office building where hand washing is the primary use for the hot water, and gas is not usually available inside the building.

Small Appliances

- Learn how much power they use, and turn them off when not in use. This may seem oversimplistic, but it is important to appreciate the difference in energy consumption among appliances. A hair dryer will use in five minutes the same energy used by a personal computer in an hour.
- Some kinds of high-tech electronic equipment have power-saver circuitry that turns off the high-energy-consuming parts if the circuits are not being used; check for these features when making a purchase. It would be great if all energy devices were so sophisticated. I had an office once with an "intelligent light switch" that would monitor the sound in the office and if it was quiet for five minutes, it would turn the lights off. I thought this was great; I could just clap my hands and the lights would turn on again.
- Explore technical alternatives. For example, all laser printers (and photocopy machines) have internal heaters that melt the powdered ink onto the paper; when on, these devices are using over 100 W keeping the heater ready to print, and adding heat to your office. In contrast, ink-jet printers use a fraction of a watt when not printing, and when printing they only use ~30 W.

What Do We Do, Short Term?

Let the short term be ten years.

Practice energy conservation religiously. Develop a consciousness of the energy use around you and eliminate waste. If no one is in the room, turn off the lights. Don't boil a pot of water to make a cup of tea. In winter dress warmly and keep the thermostat set low; vice versa in the summer. Use ink-jet printers in the office.

Eschew the automobile. Every time you approach your car ask yourself whether the trip is really necessary or whether it could be combined with other errands.

Insulate your house. Install multipane windows or storm windows. Replace the weather seal around the doors if needed. Add attic insulation if needed.

Convert your lights to more energy-efficient bulbs. You will find a wide variety of compact fluorescent and halogen light bulbs at your local hardware store that will directly replace your tungsten bulbs.

Support politicians who will make wise energy-use policy. We need policies that will reduce the consumption of oil, reduce carbon dioxide emissions, encourage energy conservation, and support research into alternate energy sources.

Educate everyone in wise energy use. Be a good example, stay informed about emerging technologies and policies, and be a dedicated advocate and spokesperson.

Purchase wisely. Research alternative technologies, then research product energy efficiencies. Be willing to pay a little more for innovative products. Be the first in your neighborhood to own an electric bicycle, and use it.

Reduce population growth. Some thing there are already more people on the earth than can be sustained; ultimately, we need to reduce human population, but the first step is to reduce the growth.

What Do We Do, Intermediate Term?

Let the intermediate term be 50 years.

Continue all of the short-term tasks.

Build or buy a fully efficient home. A superinsulated, fully efficient home will use one-tenth the energy of the average home today. If everyone would do this the energy savings would be tremendous.

Telecommute to work. The trend toward telecommuting is beginning and should be encouraged for those jobs that are compatible. Even telecommuting a couple of days a week can reduce automobile usage by nearly half.

Retire your last gasoline-powered automobile. You will have improved public transportation and will own several electric vehicles to use for local transportation.

Promote the development of fuel cells. Fuel cells, as used in spacecraft, convert chemical energy (hydrogen and oxygen) directly into electrical energy—somewhat like a battery with two fuel lines for charging. The energy transform avoids going through a heat cycle; the energy quality temperature remains high and the transform is highly efficient. The output of the fuel cell is drinkable water; hence, it provides both electricity and water for the astronauts.

Promote the use of photovoltaic solar cells. This solar energy technology transforms visible light into DC electricity with an efficiency of ~12%. Solar cells are widely used in remote locations and for low power applications. You have probably seen them mounted on emergency telephones along the roadside. The prize for innovative use of solar cells goes to Sugarite Canyon State Park near Raton, New Mexico. It has solar-powered pit toilets. The solar cells operate ventilation fans and charge batteries during the day; at night the batteries operate lights. We are just getting started in finding innovative uses for solar cells.

Promote the use of biomass energy. A growing use for petroleum is in chemicals: plastics, synthetic fibers, lightweight strong materials for manufacturing, etc. Trees can provide substitute chemicals for this use of petroleum. Trees and other plants are nature's way of storing solar energy. If we reforest the earth rather than deforest it, we can grow biomass energy.

Stop population growth. If we could immediately accomplish "replacement fertility" worldwide, which limits each couple to two children, the global population would still continue to grow for the next 50 years, barring a catastrophic war or plague. This is because there are so many children now alive who will mature into the childbearing period of their lives.

What do we do—long term?

The long term is greater than 100 years. There is only one energy source for the earth that is truly sustainable—the sun. In this time frame, we must study how to "farm" solar energy in a variety of ways.

Continue all of the intermediate-term tasks.

Photovoltaics. These systems can be used on a small scale almost anywhere. A large energy farm of them would require a dry climate.

Solar thermal. A large "farm" of mirrors focuses sunlight onto a boiler, creating steam to drive electric generators. It would be practical in very dry climates with lots of cloud-free days.

Biomass farms. These are large farms of fast-growing trees that convert sunlight into solid chemical energy, building materials, and chemical feed stocks for cellulose refineries. This technology is appropriate for wet climates.

Ocean thermal. Sunlight warms the ocean surface, but the water at the bottom is usually very cold. This temperature difference can be used to drive electric generators—sort of like operating a refrigerator backwards. This is not very efficient, but the ocean is a very large solar collector. This technology is appropriate for islands and some coastal locations.

Wind. Solar energy drives the winds, so the atmosphere is the solar collector for wind energy. Wind power could be used wherever the wind blows fast and regularly.

Hydrogen fuel. How do we store solar energy for use at night? One way is to use solar electrical energy to separate hydrogen and oxygen by electrolysis during the day and use these gases at night to produce electricity in fuel cells.

Solar design. We like to think of solar design, also called passive solar building, as something new, something that we are inventing in the latter half of the 20th century. We are actually rediscovering it in a modern context. You should visit the pueblo cities of the Anasazi in the Southwest to see how an intelligent people can use solar design to create comfortable buildings in a harsh environment with no energy but the sun and small wood fires. Visit Chaco Canyon and Bandelier National Monument in New Mexico to study the solar designs of these ancient people. We know how to use solar design now, but in the long term we will *have* to use it. There will be many innovations in materials and technology, and systems and components will be commonly available at the local building material store.

Synthetic photosynthesis. This proposal is to construct large energy farms in which the chemistry that takes place during photosynthesis is synthesized in liquids flowing through transparent tubes. The fuel (carbohydrate?) is removed from the stream, which is recharged with carbon dioxide and water and then exposed again to sunlight. Personally, I would prefer growing a forest in the same area; after all, nature has been working on this process for a couple of billion years.

Reduce the human population. Energy is not the only component in the earth system that is in short supply; others are clean water, good soil, wholesome food, housing, education, garbage dumps, etc. Sustainable living is not an option that we select like the octane of the gasoline that we pump into our automobiles; sustainable living is an absolute necessity for long-term survival of our culture. When informed and wise persons are asked, "How many humans can live on the earth in a sustainable culture?" the reply is usually a number between 4 and 5 billion, maximum. Even if we are able to stop population growth, the human population will peak at 12 billion around AD 2050. If we are to *have* a long-term future, we will need to reduce the population from 12 back down to about 4 billion. I doubt that we will do this voluntarily; I suspect that the microbes and viruses will come to the aid of Mother Nature and reduce the population in a rather unpleasant manner.

Follow the Sun

Homo sapiens sapiens (that's us) have been around for at least 30,000 years, and some anthropologists say 100,000 years. Our only energy source during most of this history was the sun and solar derived sources: biomass, wind, and water. Fossil fuels were first exploited in the last century and will be practically exhausted in the next century or the one following. For 99.8% of our history we were solar powered; we are beginning the transition to return to solar power. Vaclav Smil, in his book *General Energetics*, says:

"We are living in an energetic interlude: the stores powering our way of life are finite and even the best conversion efficiencies and conservation measures cannot extend their life beyond several hundreds of years. But it is highly improbable that we will actually go on to exhaust all of their recoverable reserves. Long before reaching that point we will either go back to flows harnessed in ways superior to preindustrial practices, or we will become dependent on another class of stores. But the past advances of global industrial civilization and its prospects for many generations to come are defined by its consumption of fossil fuels."

It is my hope that we will return to the sun as our energy source; note that I said return rather than "go back," because we will be going forward not backwards to a primitive lifestyle. The earth can be a beautiful place to live with 4 billion or fewer people living on solar energy. I don't think I would like living in a world with 12 billion people using nuclear power as the energy source. Let's "Follow the sun."

Appendix I

Force, Work, and Energy

I think we all know what a force is; it is the property in nature that tries to alter the motion of things. Gravity is a force, and it is shared by all objects in the universe. It causes the planets to move in orbits around the sun and a dropped book to fall to the floor. There are many other forces (electric, magnetic, friction, etc.); for each force there is an associated work and an associated energy. The stretching of a spring requires a force and performs work (active energy); that work is stored as energy in the spring for later use (passive energy).

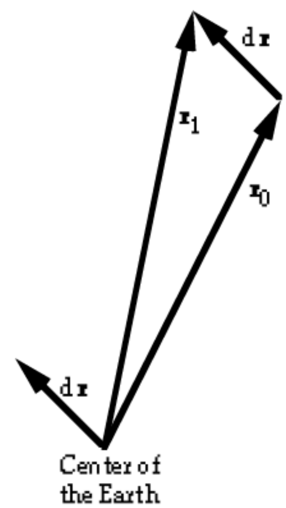
Forces (**F**) are vector properties; they have magnitude and direction (e.g., weight and downward). I will use bold letters to denote vectors in this appendix. The vector nature of forces is essential. It makes no sense to push on something unless that push has a direction. Motion or velocity (**v**) is also a vector; an object cannot move in all directions at once but must move in one particular direction at a given moment.

If an object has an initial position $\mathbf{r}_0$ and moves to a final position $\mathbf{r}_1$, then we define the object's displacement (dr) as

$$\mathrm{dr} = \mathbf{r}_1 - \mathbf{r}_0 \qquad \text{(A1)}$$

Position and displacement are also vectors because they are measured relative to some common origin. If we are using the center of the earth for the origin, position can be specified by the object's latitude, longitude, and altitude, and the position vector would correspond to an arrow pointing from the center of the earth to the position specified.

In the next column we have drawn vectors as arrows, with the magnitude of the vector specified by the length of the arrow and the direction specified by the pointing of the arrow. The position vectors $\mathbf{r}_0$ and $\mathbf{r}_1$ are drawn with their tails at the center of the earth and their points at the locations specified by the latitudes,



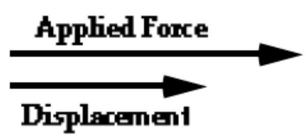
longitudes, and altitudes (measured from the center of the earth) of the positions. The displacement vector dr is drawn between the points of vectors $\mathbf{r}_0$ and $\mathbf{r}_1$ with its tail at the starting position $\mathbf{r}_0$ and its point at the final position $\mathbf{r}_1$. The vector dr with its tail at the center of the earth is mathematically equivalent to the vector dr between $\mathbf{r}_0$ and $\mathbf{r}_1$; it has the same length and orientation. We can rearrange Equation A1 to reveal the rule for adding vectors, $\mathbf{r}_1 = \mathbf{r}_0 + \mathrm{dr}$. The vector dr is added to the vector $\mathbf{r}_0$ by placing the tail of dr on the point of $\mathbf{r}_0$ and preserving the length and orientation of both vectors in the process.

Work, W, is performed on an object by exerting a force **F** and moving the object through a displacement dr, which is parallel to the force. The equation for this is:

$$W = \mathbf{F} \bullet \mathrm{dr} \qquad \text{(A2)}$$

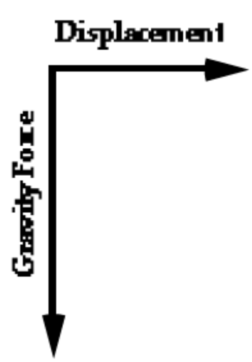
In this equation the • between F and dr means to multiply the parallel components of F and dr; it is called the "dot product" of the two vectors. We may also write this equation $W = |F| \times \cos\theta \times |dr|$, where θ is the angle between the two vectors, because multiplying by Cos θ resolves or computes the parallel components of the two vectors. Another consequence of taking the dot product of two vectors is that the result is a scalar, which has magnitude but does not have a direction. Work is a scalar quantity. The vertical bars around F and dr in the equation above mean one must use the magnitude of the vector in the computation.

In the example illustrated with the vector diagram below, we have the case in which the applied force is parallel to the displacement. A crane lifting a load typifies this case; all of the effort goes into work.



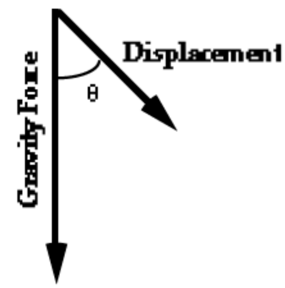
W = | Applied Force| × | Displacement|

In the next example we are depicting the case in which the displacement is perpendicular to an applied force, gravity. Here the force does no work during this displacement. There are no parallel components of force and displacement, and Cos θ = 0. The force of gravity does no work on a billiard ball rolling across a horizontal table; friction does the work in slowing the ball.



W = 0

If we consider this previous example but now we tilt the table, gravity goes into action.



W = | Gravity Force| × Cos θ × | Displacement|

In this case there is a component of the displacement parallel to gravity. Gravity performs work on the billiard ball, and its speed increases as it rolls down the sloping table.

Mechanical Potential Energy

In the main text we use the example of lifting a book, then allowing it to fall. Here we go through the formal procedure of computing the work involved in this example.

We can compute how much of the total energy involved in lifting the book remains stored as gravitational potential energy. The force of gravity acting on the book, F_g, is

$$F_g = -mg\mathbf{k} \qquad \text{(A3)}$$

where m is the mass of the book and g is the acceleration of gravity ($g \approx 9.8\ m/s^2$). The vector **k** is called a unit vector because its magnitude is always 1. The unit vector **k** is always pointed upward; therefore we include the minus sign in Equation A3 to indicate that the force of gravity is downward. The force that you apply to lift the book has to be upward (opposite to the gravity force) and slightly larger than the gravity force. In order to get the book to move upward there must be a net upward force. If the applied force and the gravity force are exactly the same size, the book does not move; this is the case when the book is stationary on the floor or the table. The force you apply to the book, F_b, can be written

$$F_b = (mg + \varepsilon)\mathbf{k} \qquad \text{(A4)}$$

The new symbol ε (epsilon) means a very small quantity compared to mg.

Now that we have the book moving upward, we need to know the displacement in order to compute the work. The height of the table is represented by h; thus the displacement, dr, can be written

$$dr = h\mathbf{k} \qquad (A5)$$

which is a simple upward displacement of h.

The work can now be computed

$$W = \mathbf{F}_b \bullet dr = mgh + \varepsilon h \qquad (A6)$$

(Since **k** is a unit vector, **k** • **k** = 1.) Our computed work has two terms in the answer. The second term depends upon ε, the additional force that you applied to get the book moving. We can identify this term with the kinetic energy of the book. The size of the second term depends upon how fast you want to move the book; if you are patient and move the book slowly then the kinetic energy term will be very small ($KE \; \mu \; v^2$). In Chapter 2 of this module we identify this second energy term as the required waste energy.

The first term of the answer in Equation A6, mgh, is completely independent of how the book is moved to the top of the table. This term depends only on the force of gravity on the book, mg, and the height of the table, h. This term, mgh, is the gravitational potential energy, GPE. As long as the book rests on the table this energy is stored and available for use; it is passive energy.

$$GPE = mgh \qquad (A7)$$

Is all of the gravitational potential energy recoverable? We can demonstrate that all of the energy is available by computing the work done by gravity when the book is allowed to fall to the floor. Equation A3 gives the gravity force, and the displacement is downward for the falling book; therefore

$$dr = -h\mathbf{k} \qquad (A8)$$

The work done by gravity in returning the book to the floor during the fall is

$$W = \mathbf{F}_g \bullet dr = mgh \qquad (A9)$$

All of the GPE is recovered by letting the book free fall to the floor. Where is the energy? Just before the book strikes the floor, the energy is all in the form of kinetic energy. Designating the speed of the book as it reaches the floor as –u, the kinetic energy is $KE = mu^2/2$; this is equal to the GPE of the book on the table, GPE = mgh.

We have looked at the two extreme situations for the book. At rest on the table the KE = 0, and all of the energy is GPE. At the end of the fall GPE = 0, and all of the energy is KE. The intermediate solutions are rather straightforward. The total energy TE = mgh when all of the energy is GPE and KE = 0. At some intermediate point during the fall when the book is at height z and has speed –w, the sum of the GPE and KE must add to give the TE.

$$\begin{aligned} TE &= GPE + KE \qquad (A10) \\ TE &= mgh \\ GPE &= mgz \\ KE &= mw^2/2 \end{aligned}$$

$$mgh = mgz + mw^2/2 \qquad (A11)$$

In our discussion above we have used the concept of conservation of energy; we said that at the end of the fall all of the energy had to be kinetic energy. We are ignoring the frictional forces, which are small for this problem, but for other situations that we will consider they become important. Equation A11 is a general statement for nonpowered objects without friction; it applies to projectiles, spacecraft, planets, and falling books. In Equation A11 we used a constant acceleration of gravity, g; therefore the equation applies to nonpowered objects without friction operating near the earth's surface.

There is an arbitrary factor in specifying GPE—the level or height at which GPE is zero. In the lifting and falling book example we set the zero level to be at floor level. For an airplane or a space shuttle, the altitude of the landing strip is the relevant zero level. For the shuttle in orbit, the center of the earth becomes the reference point for GPE.

Appendix II

Magnetics

We have not treated magnetic forces and magnetic energy as a separate entity in this book because they only enter the story as an intermediary in the transformations of electrical energy. Magnetic forces are created when electric current flows. Since electrical power systems have been designed to minimize the current in order to minimize line losses, the magnetic forces associated with power lines are not large. However, electrical devices such as motors, generators, transformers, relays, doorbells, etc., that need to convert electrical power into a force must utilize the magnetic force produced by the current in the wire to work. All such devices use many windings of the wire to multiply the magnetic force contributed by a single winding; then a magnetic material such as iron is inserted into the windings to make it more intense where it is needed. (Such components are called electromagnets, and the magnetic force disappears when the current is turned off, as opposed to permanent magnets, which are made from magnetized materials and do not require an electric current.) The magnetic force is then expressed on another magnet and causes it to move; thus, we can make motors rotate and doorbells ring. Only magnets (electro- or permanent) can feel the magnetic force. When the magnetic field is changing, the magnetic force is felt by electric charges producing electric current.

Another property of the magnetic force is as important as the motor function described above, and that is that the relationship between currents, forces, and motions is completely reversible. If we move a magnet near a wire we can cause a current to flow in the wire. If we use the wire to make many windings and insert magnetic materials to intensify the magnetic force, then we increase the current produced by moving the magnet. This is the basic operational principle of generators; we rotate strong magnets inside the generator windings and create the electric current that we use for power. Does this sound like a motor designed backwards? It should, because fundamentally the two devices are the same; in modern implementations they have been optimized to perform one function or the other. A motor uses electric current to rotate a shaft, which delivers mechanical energy; a generator's shaft is rotated using mechanical energy and it generates electric current.

The 60 Hz frequency of the electricity that we use is a result of the number of poles or separate windings in the generator and the speed at which the shaft is rotated. At every power generating station there are many generators, and on a large power grid there are many generating stations. Every single generator in this entire system must rotate at precisely the same speed, and the rotational position of each and every shaft must be exactly coordinated, or the system will not work. It is interesting to watch an operator bring a generator onto the system. The speed is adjusted using a throttle on the machine that is driving the generator; the voltage is adjusted by controlling the current to the electromagnets on the shaft; and the phase (the rotational angle of the shaft) is adjusted by "tweaking" the throttle. When all three parameters of the new generator (speed, voltage, and phase) exactly match those of the grid, the new generator is connected to the grid. Once connected, automated feedback systems will keep all generators in step; other protective devices will disconnect generators that can't stay precisely on track.

Suppose we have a motor that runs on 120 V power, and we directly connect its shaft to the shaft of a generator that produces electrical current at 480 V. We will have a device that transforms 120 V electricity to 480 V electricity when running. Such devices are used today when we need to go from DC to AC or vice versa, since motors and generators can be made to run on either type of system. This mechanical device is not the best way to change voltages on an AC system. The motor creates a magnetic force to turn the shaft, and the generator uses the turning shaft to create an alternating magnetic force on the generator windings, which generate the output current from the generator. If we eliminate the middleman and use the magnetic force from the motor side (called the primary) to directly produce the alternating magnetic force on the windings of the generator side (called the secondary), we get the same result without any moving parts and at greater efficiency. This is a transformer.

Appendix III

Standing Waves

Standing waves were introduced in the section "Antennas and EM Radiation" in Chapter 1. Here we take a closer look at standing waves, including the mathematical development. If we represent the AC voltage applied to the antenna with the sine function

$$V = V_0 \, \mathrm{Sin}(2\pi ft) \qquad (A12)$$

then we can easily find the function for the charge using Equation 3:

$$Q = C \times V_0 \, \mathrm{Sin}(2\pi ft) \qquad (A13)$$

The current to the antenna determines the rate at which the charge on the antenna changes; in other words, the current is the time derivative of the antenna charge.

$$I = dQ/dt = 2\pi f \, C \, V_0 \mathrm{Cos}(2\pi ft) \qquad (A14)$$

We can see an important behavior of antennas in Equations A12 and A14 and in Figure 2 (p. 13), which is a graph of these two equations. The voltage and the current are out of phase; when the voltage is greatest the current is zero, and when the current is greatest the voltage is zero. Antennas, which we are treating here as simple capacitors, are very different from resistors. When current flows through a resistor it is always in phase with the applied voltage. When charged, the electrical force, which is also called the electric field, extends outward from the antenna, and when the current flows in the antenna the magnetic force or field extends from the antenna. With the proper instruments the electric and magnetic fields can be sensed in the space around the antenna.

Now let us consider a very different situation in which the antenna or wire is infinitely long. When the AC voltage applied by the generator current is injected into the end of the wire, the current travels as a wave down the wire with the speed of light, c. As the AC generator goes through its sinusoidal cycle the current injected into the wire follows a sine function as depicted in Figure 2; all of these changes also propagate down the wire with the speed of light. The phenomenon of the AC signal (both current and voltage) propagating down the wire is an electromagnetic wave. The equation for the wave may be written

$$V_r = V_0 \, \mathrm{Sin}(2\pi ft - 2\pi x/\lambda) \qquad (A15)$$

where x is distance along the wire, and the wave is propagating in the direction of increasing x—to the right. In this equation λ is the wavelength; it is the distance between two adjacent peaks in the wave. Wavelength, frequency, and the speed of propagation have a simple relationship

$$c = f \times \lambda \qquad (A16)$$

If Equation A15 represents a wave propagating to the right in the wire, a wave of the same frequency and amplitude propagating to the left would be described by

$$V_l = V_0 \, \mathrm{Sin}(2\pi ft + 2\pi x/\lambda) \qquad (A17)$$

Only the sign of the second term changed. If both of these waves are present in the wire, the voltage, V_s, will be given by the sum of the two waves; after a little trigonometry we find that the voltage is

$$V_s = 2V_0 \mathrm{Sin}(2\pi ft) \, \mathrm{Cos}(2\pi x/\lambda) \qquad (A18)$$

One thing that we notice is that the amplitude of the wave is doubled, which is not surprising because we added two waves together. What is a surprise is that this combined wave no longer appears to be propagating; it now appears to remain at a fixed position on the wire, where it continues to oscillate. The peaks (antinodes) and the zeros (nodes) do not move along the wire; their position is controlled by the cosine factor of the function in Equation A18, while the oscillation of the wave is controlled by the sine factor. These waves are called stationary or standing waves, and they are relatively easy to create by reflecting a propagating wave and reversing its direction, which yields two identical waves propagating in opposite directions. Most musical instruments work on this principle of creating a standing acoustic wave on a string or in a horn.

You might well ask, "Why does the wave reflect at the end of the antenna?" Recall that there is a current wave as well as the voltage wave. When the current wave arrives at the end of the antenna there is nowhere for it to go; by definition, the current is zero at the end of the wire. The accumulation of charge at the end of the antenna causes an increase in the voltage, which then initiates the reflected wave in the opposite direction. If the antenna in our example has a length L, we can create a standing wave on the antenna by selecting a frequency so that the wavelength produces a node (zero) in the current at the end of the antenna. If $L = \lambda/2$ then the current at the end of the antenna will be zero. (Recall that the current is out of phase with the voltage.) Although other values of L which are multiples of $\lambda/2$ will also produce standing waves, they are less efficient as antennas. Selecting L smaller than $\lambda/2$ will also work but it is also less efficient.

The standing wave on the antenna creates oscillating electric and magnetic fields in the space around the antenna. Some of the energy in these oscillating fields propagates away as electromagnetic radiation. The electromagnetic wave propagates with the speed of light and consists of oscillating electric and magnetic force fields, whose frequency is that of the standing wave on the antenna. These waves are similar to the waves on the infinite wire described in Equation A15 and the associated discussion; however, electromagnetic waves in space can travel in all directions and do not require a wire or other medium in which to propagate.