Basic Concepts
Energy

Our material world is composed of many substances distinguished by their chemical, mechanical, and electrical properties. They are found in nature in various physical states—the familiar solid, liquid, and gas, along with the ionic "plasma." However, the apparent diversity of kinds and forms of material is reduced by the knowledge that there are only a little more than 100 distinct chemical elements and that the chemical and physical features of substances depend merely on the strength of force bonds between atoms.

In turn, the distinctions between the elements of nature arise from the number and arrangement of basic particles—electrons, protons, and neutrons. At both the atomic and nuclear levels, the structure of elements is determined by internal forces and energy.

1.1 FORCES AND ENERGY

A limited number of basic forces exist—gravitational, electrostatic, electromagnetic, and nuclear. Associated with each of these is the ability to do work. Thus energy in different forms may be stored, released, transformed, transferred, and "used" in both natural processes and man-made devices. It is often convenient to view nature in terms of only two basic entities—particles and energy. Even this distinction can be removed, because we know that matter can be converted into energy and vice versa.

Let us review some principles of physics needed for the study of the release of nuclear energy and its conversion into thermal and electrical form. We recall that if a constant force \( F \) is applied to an object to move it a distance \( s \), the amount of work done is the product \( Fs \). As a simple example, we pick up a book from the floor and place it on a table. Our muscles provide the means to lift against the force of gravity on the book. We have done work on the object, which now possesses stored energy (potential energy), because it could do work if allowed to fall back to the original level. Now a force \( F \) acting on a mass \( m \) provides an acceleration \( a \), given by Newton's law \( F = ma \). Starting from rest, the object gains a speed \( v \),
and at any instant has energy of motion (kinetic energy) in amount $E_k = \frac{1}{2}mv^2$. For objects falling under the force of gravity, we find that the potential energy is reduced as the kinetic energy increases, but the sum of the two types remains constant. This is an example of the principle of conservation of energy. Let us apply this principle to a practical situation and perform some illustrative calculations.

As we know, falling water provides one primary source for generating electrical energy. In a hydroelectric plant, river water is collected by a dam and allowed to fall through a considerable distance. The potential energy of water is thus converted into kinetic energy. The water is directed to strike the blades of a turbine, which turns an electric generator.

The potential energy of a mass $m$ located at the top of the dam is $E_p = Fh$, being the work done to place it there. The force is the weight $F = mg$, where $g$ is the acceleration of gravity. Thus $E_p = mgh$. For example, for 1 kg and 50 m height of dam, using $g = 9.8 \text{ m/s}^2$, $E_p$ is $(1)(9.8)(50) = 490$ joules (J). Ignoring friction, this amount of energy in kinetic form would appear at the bottom. The water speed would be $v = \sqrt{2E_k/m} = 31.3 \text{ m/s}$.

Energy takes on various forms, classified according to the type of force that is acting. The water in the hydroelectric plant experiences the force of gravity, and thus gravitational energy is involved. It is transformed into mechanical energy of rotation in the turbine, which is then converted to electrical energy by the generator. At the terminals of the generator, there is an electrical potential difference, which provides the force to move charged particles (electrons) through the network of the electrical supply system. The electrical energy may then be converted into mechanical energy as in motors, into light energy as in light bulbs, into thermal energy as in electrically heated homes, or into chemical energy as in a storage battery.

The automobile also provides familiar examples of energy transformations. The burning of gasoline releases the chemical energy of the fuel in the form of heat, part of which is converted to energy of motion of mechanical parts, while the rest is transferred to the atmosphere and highway. Electricity is provided by the automobile’s generator for control and lighting. In each of these examples, energy is changed from one form to another but is not destroyed. The conversion of heat to other forms of energy is governed by two laws, the first and second laws of thermodynamics. The first states that energy is conserved; the second specifies inherent limits on the efficiency of the energy conversion.

Energy can be classified according to the primary source. We have already noted two sources of energy: falling water and the burning of the chemical fuel gasoline, which is derived from petroleum, one of the main fossil fuels. To these

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1The standard acceleration of gravity is 9.80665 m/s². For discussion and simple illustrative purposes, numbers will be rounded off to two or three significant figures. Only when accuracy is important will more figures or decimals be used. The principal source of physical constants, conversion factors, and nuclear properties will be the CRC Handbook of Chemistry and Physics (see References), which is likely to be accessible to the faculty member, student, or reader.
we can add solar energy; the energy from winds, tides, or the sea motion; and heat from within the earth. Finally, we have energy from nuclear reactions (i.e., the “burning” of nuclear fuel).

1.2 THERMAL ENERGY

Of special importance to us is thermal energy, as the form most readily available from the sun, from burning of ordinary fuels, and from the fission process. First, we recall that a simple definition of the temperature of a substance is the number read from a measuring device such as a thermometer in intimate contact with the material. If energy is supplied, the temperature rises (e.g., energy from the sun warms the air during the day). Each material responds to the supply of energy according to its internal molecular or atomic structure, characterized on a macroscopic scale by the specific heat $c$. If an amount of thermal energy added to 1 gram of the material is $Q$, the temperature rise, $\Delta T$, is $Q/c$. The value of the specific heat for water is $c = 4.18 \, \text{J/g} \cdot \text{C}$ and thus it requires 4.18 J of energy to raise the temperature of 1 gram of water by 1 degree Celsius ($1^\circ \text{C}$).

From our modern knowledge of the atomic nature of matter, we readily appreciate the idea that energy supplied to a material increases the motion of the individual particles of the substance. Temperature can thus be related to the average kinetic energy of the atoms. For example, in a gas such as air, the average energy of translational motion of the molecules $E$ is directly proportional to the temperature $T$, through the relation $E = \frac{3}{2} kT$, where $k$ is Boltzmann’s constant, $1.38 \times 10^{-23} \, \text{J/K}$. (Note that the Kelvin scale has the same spacing of degrees as does the Celsius scale, but its zero is at $-273^\circ \text{C}$.)

To gain an appreciation of molecules in motion, let us find the typical speed of oxygen molecules at room temperature $20^\circ \text{C}$, or 293K. The molecular weight is 32, and because one unit of atomic weight corresponds to $1.66 \times 10^{-27} \, \text{kg}$, the mass of the oxygen ($O_2$) molecule is $5.30 \times 10^{-26} \, \text{kg}$. Now

$$E = \frac{3}{2} (1.38 \times 10^{-23}) (293) = 6.07 \times 10^{-21} \text{J}$$

and thus the speed is

$$v = \sqrt{\frac{2E}{m}} = \sqrt{2(6.07) \times 10^{-21} / (5.30 \times 10^{-26})} \approx 479 \, \text{m/s}.$$

Closely related to energy is the physical entity power, which is the rate at which work is done. To illustrate, let the flow of water in the plant of Section 1.1 be $2 \times 10^6 \, \text{kg/s}$. For each kg the energy is 490 J; the energy per second is $(2 \times 10^6) (490) = 9.8 \times 10^8 \, \text{J/s}$. For convenience, the unit joule per second is called the watt (W). Our plant thus involves $9.8 \times 10^8 \, \text{W}$. We can conveniently express this in kilowatts (1 kW = $10^3 \, \text{W}$) or megawatts (1 MW = $10^6 \, \text{W}$). Such multiples of units are used because of the enormous range of magnitudes of quantities in nature—from the submicroscopic to the astronomical. The standard set of prefixes is given in Table 1.1.
For many purposes we will use the metric system of units, more precisely designated as SI, Systeme Internationale. In this system (see References) the base units are the kilogram (kg) for mass, the meter (m) for length, the second (s) for time, the mole (mol) for amount of substance, the ampere (A) for electric current, the kelvin (K) for thermodynamic temperature, and the candela (cd) for luminous intensity. However, for understanding of the earlier literature, one requires a knowledge of other systems. The Appendix includes a table of useful conversions from British units to SI units.

The transition in the United States from British units to SI units has been much slower than expected. In the interest of ease of understanding by the typical reader, a dual display of numbers and their units appears frequently. Familiar and widely used units such as the centimeter, the barn, the curie, and the rem are retained.

In dealing with forces and energy at the level of molecules, atoms, and nuclei, it is conventional to use another energy unit, the electron-volt (eV). Its origin is electrical in character, being the amount of kinetic energy that would be imparted to an electron (charge \(1.60 \times 10^{-19}\) coulombs) if it were accelerated through a potential difference of 1 volt. Because the work done on 1 coulomb would be 1 J, we see that 1 eV = \(1.60 \times 10^{-19}\) J. The unit is of convenient size for describing atomic reactions. For instance, to remove the one electron from the hydrogen atom requires 13.5 eV of energy. However, when dealing with nuclear forces, which are very much larger than atomic forces, it is preferable to use the million-electron-volt unit (MeV). To separate the neutron from the proton in the nucleus of heavy hydrogen, for example, requires an energy of about 2.2 MeV (i.e., \(2.2 \times 10^6\) eV).

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**Table 1.1 Prefixes for Numbers and Abbreviations**

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<th>Prefix</th>
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Another form of energy is electromagnetic or radiant energy. We recall that this energy may be released by heating of solids, as in the wire of a light bulb; by electrical oscillations, as in radio or television transmitters; or by atomic interactions, as in the sun. The radiation can be viewed in either of two ways—as a wave or as a particle—depending on the process under study. In the wave view it is a combination of electric and magnetic vibrations moving through space. In the particle view it is a compact moving uncharged object, the photon, which is a bundle of pure energy, having mass only by virtue of its motion. Regardless of its origin, all radiation can be characterized by its frequency, which is related to speed and wavelength. Letting \( c \) be the speed of light, \( \lambda \) its wavelength, and \( v \) its frequency, we have \( c = \lambda v \). For example, if \( c \) in a vacuum is \( 3 \times 10^8 \) m/s, yellow light of wavelength \( 5.89 \times 10^{-7} \) m has a frequency of \( 5.1 \times 10^{14} \) s\(^{-1}\). X-rays and gamma rays are electromagnetic radiation arising from the interactions of atomic and nuclear particles, respectively. They have energies and frequencies much higher than those of visible light.

To appreciate the relationship of states of matter, atomic and nuclear interactions, and energy, let us visualize an experiment in which we supply energy to a sample of water from a source of energy that is as large and as sophisticated as we wish. Thus we increase the degree of internal motion and eventually dissociate the material into its most elementary components. Suppose in Figure 1.1 that the water is initially as ice at nearly absolute zero temperature, where water (H\(_2\)O) molecules are essentially at rest. As we add thermal energy to increase the temperature to \( 0^\circ\text{C} \) or \( 32^\circ\text{F} \), molecular movement increases to the point at which the ice melts to become liquid water, which can flow rather freely. To cause a change from the solid state to the liquid state, a definite amount of energy (the heat of fusion) is required. In the case of water, this latent heat is \( 334 \) J/g. In the temperature range in which water is liquid, thermal agitation of the molecules permits some evaporation from the surface. At the boiling point, \( 100^\circ\text{C} \) or \( 212^\circ\text{F} \) at atmospheric pressure, the liquid turns into the gaseous form as steam. Again, energy is required to cause the change of state, with a heat of vaporization of \( 2258 \) J/g. Further heating, by use of special high temperature equipment, causes dissociation of water into atoms of hydrogen (H) and oxygen (O). By electrical means, electrons can be removed from hydrogen and oxygen atoms, leaving a mixture of charged ions and electrons. Through nuclear bombardment, the oxygen nucleus can be broken into smaller nuclei, and in the limit of temperatures in the billions of degrees, the material can be decomposed into an assembly of electrons, protons, and neutrons.

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\(^{1}\) We will need both Roman and Greek characters, identifying the latter by name the first time they are used, thus \( \lambda \) (lambda) and \( \nu \) (nu). The reader must be wary of symbols used for more than one quantity.
The connection between energy and matter is provided by Einstein’s theory of special relativity. It predicts that the mass of any object increases with its speed. Letting the mass when the object is at rest be $m_0$, the “rest mass,” letting $m$ be the mass when it is at speed $v$, and noting that the speed of light in a vacuum is $c = \frac{3 \times 10^8}{s}$, then

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}.$$  

For motion at low speed (e.g., 500 m/s), the mass is almost identical to the rest mass, because $v/c$ and its square are very small. Although the theory has the status of natural law, its rigor is not required except for particle motion at high speed (i.e., when $v$ is at least several percent of $c$). The relation shows that a material object can have a speed no higher than $c$.

The kinetic energy imparted to a particle by the application of force according to Einstein is

$$E_k = (m - m_0)c^2.$$
(For low speeds, \( v \ll c \), this is approximately \( \frac{1}{2} m_0 v^2 \), the classical relation.)

The implication of Einstein’s formula is that any object has an energy \( E_0 = m_0 c^2 \) when at rest (its “rest energy”), and a total energy \( E = mc^2 \), the difference being \( E_k \) the kinetic energy (i.e., \( E = E_0 + E_k \)). Let us compute the rest energy for an electron of mass \( 9.1 \times 10^{-31} \) kg

\[
E_0 = m_0 c^2 = (9.1 \times 10^{-31}) (3.0 \times 10^8)^2 = 8.2 \times 10^{-14} \text{ J}
\]

\[
E_0 = \frac{8.2 \times 10^{-14} \text{ J}}{1.60 \times 10^{-13} \text{ J/MeV}} = 0.51 \text{ MeV}.
\]

For one unit of atomic mass, \( 1.66 \times 10^{-27} \) kg, which is close to the mass of a hydrogen atom, the corresponding energy is 931 MeV.

Thus we see that matter and energy are equivalent, with the factor \( c^2 \) relating the amounts of each. This suggests that matter can be converted into energy and that energy can be converted into matter. Although Einstein’s relationship is completely general, it is especially important in calculating the release of energy by nuclear means. We find that the energy yield from a kilogram of nuclear fuel is more than a million times that from chemical fuel. To prove this startling statement, we first find the result of the complete transformation of 1 kilogram of matter into energy, namely, \( (1 \text{ kg})(3.0 \times 10^8 \text{ m/s})^2 = 9 \times 10^{16} \text{ J} \). The nuclear fission process, as one method of converting mass into energy, is relatively inefficient, because the “burning” of 1 kg of uranium involves the conversion of only 0.87 g of matter into energy. This corresponds to approximately \( 7.8 \times 10^{13} \text{ J/kg} \) of the uranium consumed. The enormous magnitude of this energy release can be appreciated only by comparison with the energy of combustion of a familiar fuel such as gasoline, \( 5 \times 10^7 \text{ J/kg} \). The ratio of these numbers, \( 1.5 \times 10^6 \), reveals the tremendous difference between nuclear and chemical energies.

Calculations involving Einstein’s theory are made easy by use of a computer program ALBERT, described in Computer Exercise 1.A.

1.5 ENERGY AND THE WORLD

All of the activities of human beings depend on energy, as we realize when we consider the dimensions of the world’s energy problem. The efficient production of food requires machines, fertilizer, and water, each making use of energy in a different way. Energy is vital to transportation, protection against the weather, and the manufacturing of all goods. An adequate long-term supply of energy is therefore essential for man’s survival. The world energy problem has many dimensions: the increasing cost to acquire fuels as they become more scarce; the potential for global climate change resulting from burning fossil fuels; the effects on safety and health of the byproducts of energy consumption; the inequitable distribution of energy resources among regions and nations; and the discrepancies between current energy use and human expectations throughout the world.
1.6 SUMMARY
Associated with each basic type of force is an energy, which may be transformed to another form for practical use. The addition of thermal energy to a substance causes an increase in temperature, the measure of particle motion. Electromagnetic radiation arising from electrical devices, atoms, or nuclei may be considered to be composed of waves or of photons. Matter can be converted into energy and vice versa according to Einstein’s formula $E = mc^2$. The energy of nuclear fission is millions of times as large as that from chemical reactions. Energy is fundamental to all human endeavors and, indeed, survival.

1.7 EXERCISES
1.1 Find the kinetic energy of a basketball player of mass 75 kg as he moves down the floor at a speed of 8 m/s.
1.2 Recalling the conversion formulas for temperature,
\[ C = \frac{5}{9}(F - 32) \]
\[ F = \frac{9}{5}C + 32 \]
where $C$ and $F$ are degrees in respective systems, convert each of the following: 68°F, 500°F, −273°C, 1000°C.
1.3 If the specific heat of iron is 0.45 J/g-°C, how much energy is required to bring 0.5 kg of iron from 0°C to 100°C?
1.4 Find the speed corresponding to the average energy of nitrogen gas molecules ($N_2$, 28 units of atomic weight) at room temperature.
1.5 Find the power in kilowatts of an auto rated at 200 horsepower. In a drive for 4 h at average speed 45 mph, how many kWh of energy are required?
1.6 Find the frequency of a γ ray photon of wavelength $1.5 \times 10^{-12}$ m.
1.7 (a) For very small velocities compared with the velocity of light, show that the relativistic formula for kinetic energy is $(1/2)mv^2$. Hint: use the series expansion
\[(1 + x)^n = 1 + nx + \ldots.\]
(b) Find the approximate relativistic mass increase of a car with rest mass 1000 kg moving at 20 m/s.
1.8 Noting that the electron-volt is $1.60 \times 10^{-19}$ J, how many joules are released in the fission of one uranium nucleus, which yields 190 MeV?
1.9 Applying Einstein’s formula for the equivalence of mass and energy, 
\[ E = mc^2, \] 
where \( c = 3 \times 10^8 \text{ m/s} \), the speed of light, how many kilograms 
of matter are converted into energy in Exercise 1.8?

1.10 If the atom of uranium-235 has mass of (235) \( (1.66 \times 10^{-27}) \) kg, what 
amount of equivalent energy does it have?

1.11 Using the results of Exercises 1.8, 1.9, and 1.10, what fraction of the mass 
of a U-235 nucleus is converted into energy when fission takes place?

1.12 Show that to obtain a power of 1 W from fission of uranium, it is necessary 
to cause \( 3.3 \times 10^{10} \) fission events per second. Assume that each fission 
releases 190 MeV of useful energy.

1.13 (a) If the fractional mass increase caused by relativity is \( \Delta E/E_0 \), show that 
\[ \frac{v}{c} = \sqrt{1 - \left(1 + \frac{\Delta E}{E_0}\right)^{-2}}. \]
(b) At what fraction of the speed of light does a particle have a mass that is 
1% higher than the rest mass? 10%? 100%?

1.14 The heat of combustion of hydrogen by the reaction \( 2\text{H} + \text{O} = \text{H}_2\text{O} \) is 
quotted to be 34.18 kilogram calories per gram of hydrogen. (a) Find how 
many Btu per pound this is with the conversions 1 Btu = 0.252 kcal, 
1 lb = 454 grams. (b) Find how many joules per gram this is noting 1 
cal = 4.18 J. (c) Calculate the heat of combustion in eV per H\(_2\) molecule. 
Note: Recall the number of particles per gram of molecular weight, Avogadro’s number, \( N_A = 6.02 \times 10^{23} \).

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**COMPUTER EXERCISES**

1.A Properties of particles moving at high velocities are related in a complicated 
way according to Einstein’s theory of special relativity. To obtain answers 
easily, the computer program ALBERT (after Dr. Einstein) can be used to 
treat the following quantities:

- Velocity
- Momentum
- Total mass-energy
- Kinetic energy
- Ratio of mass to rest mass

Given one of the above, for a selected particle, ALBERT calculates the others. 
Test the program with various inputs, for example \( v/c = 0.9999 \) and \( T = 1 \) 
billion electron volts.
1.8 GENERAL REFERENCES

Encyclopedia Britannica online, http://www.britannica.com
Brief articles are free; full articles require paid membership.

Millions of articles in free encyclopedia. Subject to edit by anyone and thus may contain misinformation.


Radiation Information Network
http://www.physics.isu.edu/radinf
Numerous links to sources. By Bruce Busby, Idaho State University.

American Nuclear Society publications
http://www.ans.org

American Nuclear Society public information
http://www.ans.org/pi
Essays on selected topics (e.g., radioisotope).


WWW Virtual Library
http://www.vlib.org
Links to Virtual Libraries in Engineering, Science, and other subjects.

WWW Virtual Library Nuclear Engineering
http://www.nuc.berkeley.edu/main/vir_library.html
Alsos Digital Library for Nuclear Issues
http://alsos.wlu.edu
Large collection of references.

How Things Work
http://howthingswork.virginia.edu
Information on many subjects by Professor Louis Bloomfield.

How Stuff Works
http://www.howstuffworks.com
Brief explanations by Marshall Brain of familiar devices and concepts, including many of the
topics of this book.

Internet Detective
http://www.vts.intute.ac.uk/detective
A tutorial on browsing for quality Internet information.

Energy Quest
http://www.energyquest.co.gov/story/index.html
The Energy Story. From California Energy Commission.

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http://physics.nist.gov/cuu/
Information on SI units and fundamental physical constants.

American Physical Society
http://www.aps.org
Select Students & Educators/Physics Central.

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http://www.particleadventure.org
By Lawrence Berkeley National Laboratory.

PhysLink
http://www.physlink.com
Select Reference for links to sources of many physics constants, conversion factors, and
other data.

Physical Science Resource Center
http://www.psrc-online.org
Links provided by American Association of Physics Teachers. Select Browse Resources.
Antimatter: Mirror of the Universe
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Albert Einstein
http://www.westegg.com/einstein
http://www.pbs.org/wgbh/nova/einstein
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