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1 Introduction

CONTENTS

1.1 What is Thermodynamics?

Thermodynamics is the science of energy and its transformations. Engineering thermodynamics is the application of this science in the creation of new technology. It must be understood very well by engineers of all varieties. A basic understanding of thermodynamics can also be an asset to people in fields where the technology is used, such as medicine, and to any lawyer, politician, or citizen who participates in decisions on the appropriate uses of technology. Thermodynamic analysis provides a good model for general analytical thinking.

Basic principles

Like any science, thermodynamics rests on a small number of very fundamental principles. The *First Law of Thermodynamics* is the idea that energy is conserved; this means that the total energy in any isolated region is always the same, although the form of the energy may change. It is one of the two great conservation principles on which all of modern science rests (the other is conservation of momentum). These conservation principles cannot be proven by experiment because the things one measures in an experiment are evaluated by assuming that the principles are true. But by using the basic principles, if necessary inventing new forms of energy to keep energy conserved, or new forces to keep momentum conserved, we can explain the workings of nature and create devices that behave as we predict, and that give support to the theory.

Microscopic and macroscopic views

Energy exists at all scales, from the smallest subatomic scale to the grandest scale of the universe. At human scales we sense that fast-moving objects have lots of *kinetic energy*, and that heavy objects up high, springs wound up, or charged capacitors have lots of *potential energy*. We also sense that a very hot object has much energy, in modern terminology referred to as *internal energy* (not *heat*, which in modern terminology refers to a mechanism of energy *transfer* and not to energy *content*). At *microscopic* scales, internal energy is nothing more than the kinetic and potential energy of the molecules, which we cannot see in detail at our human *macroscopic* scale. The energy in the electronic bonds that hold molecules together is another form of *internal energy*.

When a macroscopic object is moving quickly, there is a high degree of organization in the motion of the molecules. In contrast, the object could be

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motionless but contain the same energy, this time in randomly oriented, disorganized molecular motions (internal energy). Often the job of an engineer is to find some way to convert microscopically *disorganized* energy (internal energy) into microscopically *organized* energy (kinetic or potential energy) so that we can produce a macroscopic motion or effect. There is a limit on the ability of macroscopic systems to produce microscopic order. The *Second Law of Thermodynamics* is the great principle of science that reflects this limit.

Entropy

Just as the first law is based on a fundamental property of matter (energy) so is the second law, which rests on the concept of *entropy*. Entropy is a measure of the *amount of microscopic disorder* in a macroscopic system. The second law says that *entropy can be produced, but is never destroyed*. In other words, molecules left to themselves will not become organized; all natural processes produce entropy. This law has been supported by more than a century of accurate predictions for the behavior of macroscopic systems, and in more recent times by new understanding of the dynamics of nonlinear systems with many degrees of freedom, which are known to exhibit chaotic behavior.

These two fundamental principles (first and second laws) are mostly what thermodynamics is all about. The first law gives us valuable equations to use in predicting the behavior of something we might like to build. But it does not tell us whether or not the processes we assumed would occur will actually take place or could take place. This missing information is provided by the second law, which tells us which way a process must go. Used together in combination in a technique called *exergy (or availability) analysis*, they can tell us the minimum electrical power required to liquefy a given stream of natural gas, or the maximum shaft power we could get out of the chemical energy in a barrel of oil, *without any reference to the sort of hardware we might employ in these systems*. This gives us the "best performance" against which we can compare the systems we design to see how much margin there might be for improvement. Thus, thermodynamics is an extremely powerful tool and one that an engineer should not be without.

Our approach

There are many approaches to teaching thermodynamics. The biggest differences surround the way in which the second law is approached. There are some who prefer a logically elegant, purely macroscopic approach in which entropy is given no microscopic interpretation and hence is purely a mathematical abstraction. Beginning students usually find this nonphysical approach very difficult to comprehend, and this often results in thermodynamics courses being regarded as mystery hours. Instead we will use an approach in which almost all of our work is *macroscopic* but much of our thinking builds on our understanding of the *microscopic* nature of matter. We believe that our approach will enable you to grasp the basic principles of thermodynamics quickly, to use them effectively in engineering analysis, and to explain the results of your analysis.

1.2 Accounting for the Basic Quantities

Much of engineering analysis involves the application of a basic principle to a carefully defined system, which yields an equation that describes something fundamental about the behavior of the system. There are two distinct steps in such an analysis. The first step is simply an accounting of the flows of the quantity in the principle (mass, energy, momentum, or entropy). The second step is to invoke the physics of the principle.

Production accounting

A very nice way to express the accounting is in terms of *production*. The production of anything by a system (automobiles by a factory, money by a bank account, momentum by a jet engine, energy by a power station, or entropy by a chemical reaction) is given by

$$\textbf{production} = \textbf{output} - \textbf{input} + \textbf{accumulation}. \quad (1.1a)$$

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The *accumulation* is the increase in the amount within the system, or equivalently the excess of the final amount over the initial amount within the system,

$$\textbf{accumulation} = \textbf{final} - \textbf{initial}. \tag{1.1b}$$

For your bank account, "output" is your withdrawals plus bank charges, "input" is your deposits plus bank interest payments, "accumulation" is the increase in your balance, and "production" is zero (unless your bank prints new money and gives you some), *all measured over the same time period. This is the most important equation to master for success in engineering thermodynamics*. If you can balance your checkbook, you should have no trouble with this basic accounting equation.

Rate-basis production accounting

Sometimes we make our balances over a definite time interval (as above), and other times we make our balances on a *rate basis*, therefore we have that

$$\textbf{rate of production} = \textbf{rate of output} - \textbf{rate of input} + \textbf{rate of accumulation}. \tag{1.1c}$$

Given that the application of the balance results in an ordinary differential equation, and that the time-derivative is commonly at the left-hand side of the equation, we can also write

$$\textbf{rate of accumulation} = \textbf{rate of input} - \textbf{rate of output} + \textbf{rate of production}. \tag{1.1d}$$

Rate-basis accounting is useful in deriving differential equations that govern the system, but it is also useful in *steady-state* problems, where the rate of accumulation is zero and all of the other rates are constants. Momentum analyses are almost always made on a rate basis, because forces are (by concept; see Section 1.3) rates of momentum transfer.

Basic principles

The production (or rate of production) of any conserved quantity must be zero. Thus, denoting production by $\mathcal{P}$, the principles of conservation of energy, and momentum can be expressed in the very simple and easily remembered forms,

$$\mathcal{P}_{\text{energy}} = 0, \tag{1.2a}$$

$$\mathcal{P}_{\text{momentum}} = 0. \tag{1.2b}$$

For the case of non-relativistic mechanics, which covers almost all that is of interest in engineering thermodynamics, mass is also conserved, so

$$\mathcal{P}_{\text{mass}} = 0. \tag{1.2c}$$

Unlike these conserved entities, entropy is produced by natural processes; in the limit of certain idealized processes (*reversible* processes) entropy is ideally conserved. So the Second Law of Thermodynamics can be expressed very neatly as

$$\mathcal{P}_{\text{entropy}} \geq 0. \tag{1.2d}$$

The four equations (1.2a)–(1.2d) concisely give the pertinent physics of engineering thermodynamics. Used in conjunction with production accounting as described above, they provide the key tools for engineering analysis.

Alternative balance equations

The accounting equation may be written in other forms equivalent to (1.1a):

$$\textbf{production} = \textbf{net output} + \textbf{accumulation}, \tag{1.3a}$$

$$\textbf{input} + \textbf{production} = \textbf{output} + \textbf{accumulation}, \tag{1.3b}$$

$$\textbf{input} + \textbf{initial} + \textbf{production} = \textbf{output} + \textbf{final}. \tag{1.3c}$$

Some students find it easier to remember one of these other forms. Production accounting, (1.1a) or (1.3a), is often preferred because the basic principles are expressed in terms of production. Equation (1.3a) is the most compact and is often preferred in advanced treatments. We like to use (1.3b) for conserved quantities (mass, energy, momentum). In (1.3c) the accumulation term is split into two pieces (*initial* and *final*), which can make some problems harder rather than easier. You should use whatever form

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seems most natural to you and is acceptable to your instructor.

1.3 Analysis Methodology

How to be systematic

It is important to develop a systematic methodology for doing analysis. Here are the steps that should be taken every time you do an engineering analysis:

1. Define the system under study by dotted lines on a sketch. Try to put the boundaries where you know something or need to know something, never where you don't know something and don't need to know something.
2. Indicate the reference frame of the observer if it is other than fixed with respect to the system dots. This is particularly important in momentum analyses.
3. List the simplifying assumptions that will be used in writing the balance.
4. Indicate the time basis for the analysis (a specific time period or a rate basis).
5. On the sketch, show all of the non-zero terms that will appear in your balance equation: include all transfers with arrows defining the direction of positive transfer, the accumulations, and any productions. This defines your nomenclature.
6. Write the basic balance for your system, in terms of the quantities defined on your sketch. There should be a one-to-one correspondence between the terms in your equation and those in the sketch. Check that only transfers across the system boundary appear in your balance equation.
7. After you have written all the pertinent balances, bring in other modeling information as necessary to bring the analysis to the point where you have the same number of equations as unknowns and can therefore (in principle) solve for the unknowns. Do this using symbols at first, then substitute numbers to get what you need.

Make your analysis readable!

A good analysis, like a good computer program, should have comments here and there to help the reader understand the various steps. Numbering the equations helps. If you learn to make your analysis "readable" with a few well-chosen words, those who read it will understand it more easily, you will save time trying to understand it when you read it in the future, and you will find it much easier to write it up for a report or journal article.

1.4 Concepts from Mechanics

We assume that the student already has a background in mechanics and has some notion of the concepts of momentum, mass, force, kinetic energy, and potential energy. These fundamentals will be important in our study of thermodynamics. In the next two sections we review these familiar ideas to set the stage for our introduction to the fundamentals of thermodynamics.

Conservation of momentum

The key fundamental principle in mechanics is the *conservation of momentum*, which incorporates the following ideas:

- Matter can be treated as having a property, called *momentum*, that is an *extensive, conserved, vector function of its velocity* measuring its tendency to keep moving in the same direction at the same speed when the matter is *not* acted upon by external agents.

The terms used above are very important and have the following meanings:

- *extensive* means that the momentum of an object is the sum of the momenta of its parts;
- *conserved* means that the momentum of an isolated system does not change;
- *vector function of its velocity* means that the momentum of a little piece of matter (a particle) is a vector that depends on its velocity vector.

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These physical ideas are enough to determine the mathematical representation of momentum. A mathematical theorem (the *representation theorem*) says that the only vector function of another vector is a scalar times the vector itself. Therefore, denoting the velocity vector of a particle by $\vec{\mathcal{V}}$ and its momentum vector by $\vec{\mathcal{I}}$, we know that the most general relationship possible between the momentum and velocity of a particle is

$$\vec{\mathcal{I}} = M(\mathcal{V}^2)\vec{\mathcal{V}}. \tag{1.4}$$

Here M is a scalar function that can depend at most on the only scalar that can be formed from the velocity vector, namely its magnitude (or magnitude-squared $\mathcal{V}^2$). Throughout this book we use a special parenthetical notation to distinguish the arguments of a function from a multiplicative factor. For example, $M(\mathcal{V}^2)$ denotes that M is a function of $\mathcal{V}^2$. As you know, we call M the *mass* of the particle.

Mass

With the addition of the basic concept of relativity, namely that the speed of light c must be the same in all reference frames, the functional form of $M(\mathcal{V}^2)$ can be determined. One considers an isolated system, in which two identical particles collide, as viewed in two different reference frames moving with respect to one another. Invoking conservation of momentum as written by observers in each frame, and using symmetry arguments and the Lorentz transformation, one discovers that the only functional form that allows momentum conservation in all frames is[1]

$$M = \frac{M_0}{\sqrt{1 - \mathcal{V}^2/c^2}}, \tag{1.5}$$

where M_0 is a constant called the *rest mass* of the particle. Note that just the basic ideas underlying the concept of momentum have led us to a formula for evaluating momentum! It is the same with energy and entropy, where careful formulations of the concepts lead to ways to measure these human representations of nature.

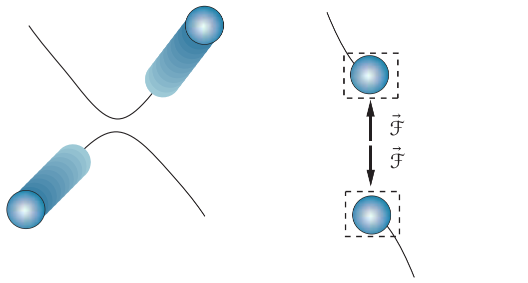
[1] See, *e.g.*, Wiedner and Sells, *Elementary Physics*, Allyn and Bacon, 1975, Ch. 35.

For a particle moving slowly compared with the speed of light, $\mathcal{V}^2 \ll c^2$ and so $M \approx M_0$. This is the realm of *Newtonian mechanics*, where mass also can be treated as a conserved quantity. Almost everything we shall do in this book is treated adequately by Newtonian mechanics, so we will make frequent use of the approximation that the mass of a particle is constant or that *mass is conserved*.

Force

When two systems interact in isolation, their combined momentum is conserved, but the momentum of one can increase while that of the other decreases by the same amount (Figure 1.1a). Often we want to analyze one system without detailed consideration of the other. We do this by drawing an imaginary boundary around the system of interest and replacing its interaction with the other system in some appropriate manner. In the case of a momentum analysis, we need to account for the possibility of momentum transfer from one to the other. As you know, we attribute this momentum transfer to a *force* acting between the two systems.

You were probably introduced to the concept of force (a push or pull) at a very early age, well before encountering the concept of momentum. You may have already studied the analysis of trusses and other static structures, using forced-based analyses that do not even mention momentum. However, at this stage in your education it is important to appreciate that the concepts of force and momentum are intimately related, and that the fundamental forces in nature have been invented to explain observed changes in momentum.



(a) Momentum exchange in a collision. (b) Forces transfer momentum.

Figure 1.1 Interactions.

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We define the force acting *on* a system as the *rate of momentum transfer to the system*. Since the momentum transfer out of the first system is exactly the momentum transfer into the second, the force acting on the first system is always equal but opposite to the force acting on the second (Figure 1.1b).

Newton's law

With this understanding of the meaning of force, Newton's law can be interpreted as the *momentum balance* on a Newtonian particle. If $\vec{\mathcal{F}}$ is the force acting on a particle, and $\vec{\mathcal{V}}$ is its velocity, the momentum balance on the particle is

$$\underbrace{\vec{\mathcal{F}}}_{\substack{\text{rate of}\\\text{momentum}\\\text{input}}} = \underbrace{\frac{d(M\vec{\mathcal{V}})}{dt}}_{\substack{\text{rate of}\\\text{momentum}\\\text{accumulation}}}. \tag{1.6}$$

If $\mathcal{V} \ll c$ then $M \approx M_0 =$ constant; since the acceleration is $\vec{a} = d\vec{\mathcal{V}}/dt$, (1.6) then becomes $\vec{\mathcal{F}} = M\vec{a}$. Note that $\vec{\mathcal{F}}$, $\vec{\mathcal{V}}$, and $\vec{a}$ are all *vectors*, and *each component of the momentum* is conserved.

Gravitation

As viewed from the Sun, the Moon is constantly changing its direction (and hence its momentum vector) as it orbits the Earth. How can we explain this? The classical way is to ascribe the perceived momentum change to a *gravitational force* between the Earth and Moon, which causes both to orbit their common center of mass. Another way is to say that the Earth and Moon move freely, each with constant momentum, in a mass-distorted space–time frame (Einstein's theory). Both are legitimate views, and both invoke conservation of momentum. Since the classical view is conceptually simpler and works adequately for virtually every engineering task, we will use the gravitational force approach.

The gravitational force between two point masses M_1 and M_2 separated by a distance r can be reasoned to be given by

$$\mathcal{F} = k_G \frac{M_1 M_2}{r^2}, \tag{1.7}$$

where $k_G = 6.67 \times 10^{-11}$ $\text{m}^3/(\text{kg} \cdot \text{s}^2)$ is a physical constant. The force exerted by the Earth on an object (its *weight*, w) can be obtained by integrating (summing) the effects of all little pieces of the Earth and object, and is

$$w = Mg \tag{1.8}$$

where M is the total mass of the object. Newton's law shows that the factor g is the acceleration of a freely-falling object, which is approximately $g = 9.8$ m/s^2 on Earth.

Inertial frames

Momentum conservation analyses must be done in an *inertial reference frame*, a coordinate system in which a free particle would accelerate at the rate determined by the external gravitational field. For some analyses (aircraft dynamics) the inertial frame can be fixed to the Earth's surface; for other analyses (satellite launch) the inertial frame may be fixed at the Earth's center; still other analyses (interplanetary trajectories) require a Sun-based coordinate system; and so on.

Momentum analysis methodology

It is important that an engineer develops a good methodology for analysis. Meticulous attention to the following steps will greatly reduce the chance for an error in a momentum analysis:

1. Draw a diagram identifying the system to be analyzed by enclosing it within dotted lines.
2. Show the inertial reference frame to be used in writing the equations.
3. List any simplifying idealizations.
4. Show all forces (or momentum transfers) acting on (or transferred to/from) the system to define their positive directions.
5. Show the velocities to define their positive directions.
6. Write the momentum conservation equation for each component direction (x, y, z) of importance; there should be a one-to-one correspondence between the forces (or momentum transfers)

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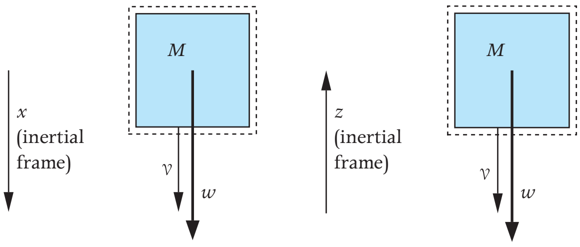

(a) System diagram for Equation (1.9a).

(b) System diagram for Equation (1.9b).

Figure 1.2 Momentum balance.

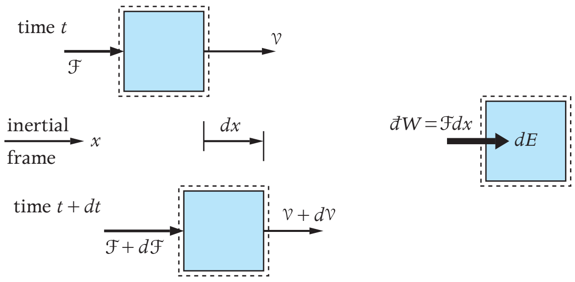

Figure 1.3 Definition of work.

on the diagram and those in the equations. The momentum balance is usually done on a rate basis.

7. Bring in other information as necessary to complete the analysis.

Example: being systematic. Let us consider a body of mass M falling freely towards the Earth (Figure 1.2a). It will accelerate as it falls due to the downward gravitational force w exerted on it by the Earth. Its momentum in the downward direction will increase as a result of the momentum transfer into the object by the downward force. We make the simplifying idealization that the resistance force exerted by the air is negligible. Then, denoting the downward velocity by $\mathcal{V}$, the balance of *downward* (x) momentum gives

$$\underbrace{w}_{\substack{\text{rate of}\\ \text{momentum}\\ \text{input}}} = \underbrace{\frac{d(M\mathcal{V})}{dt}}_{\substack{\text{rate of}\\ \text{momentum}\\ \text{accumulation}}} . \qquad (1.9a)$$

Had we chosen to write the momentum balance in the *upward* (z) coordinate system (Figure 1.2b) instead, the momentum balance of *upward* momentum would be

$$\underbrace{0}_{\substack{\text{rate of}\\ \text{momentum}\\ \text{input}}} = \underbrace{w}_{\substack{\text{rate of}\\ \text{momentum}\\ \text{output}}} + \underbrace{\frac{d(-M\mathcal{V})}{dt}}_{\substack{\text{rate of}\\ \text{momentum}\\ \text{accumulation}}} . \qquad (1.9b)$$

Note that the momentum in the z direction is $-M\mathcal{V}$, and the weight force w takes z momentum *out* of the system. The end result is the same, but using inconsistent frames for different terms would lead to errors. Being systematic helps avoid such errors.

1.5 Mechanical Concepts of Energy

Work

The concept of *work* is central in both mechanics and thermodynamics. Figure 1.3 shows an object that moves a small distance $d\vec{x}$ while force $\vec{\mathcal{F}}$ acts upon it. Note that we allow the velocity and force to change a little during this process. The work done *on* the object by the force, or the energy transfer as work *to* the object, is defined as

$$đW = \vec{\mathcal{F}} \cdot d\vec{x}. \qquad (1.10)$$

Here $đ$ is a special symbol that we use to denote *a small amount*, as opposed to the symbol d, which denotes *a small change*. Mathematically $đ$ denotes an *inexact differential*, meaning it is not the change of anything, while d denotes an exact differential, which is a change of something. Note that $\vec{\mathcal{F}}$ can vary during this process, and that $đW \neq d(\vec{\mathcal{F}} \cdot \vec{x})$. The $đ$ symbol reminds us that $đW$ is not the differential of W.

In thermodynamics, energy is conceived as a general conserved property of matter, and work as a form of energy transfer. Expressions for other forms of energy are then derived by making energy balances that relate these energy changes to work. We illustrate this in the following for two familiar forms of energy.

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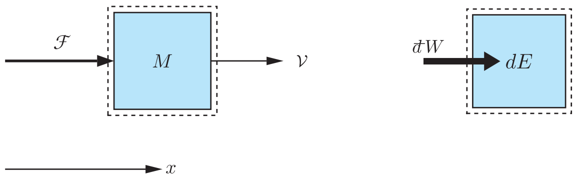


(a) Accelerating a mass increases its kinetic energy.

(b) Terms in the energy balance.

Figure 1.4 Kinetic energy balance.

Kinetic energy

Consider the acceleration of a body of fixed mass M acted on by force $\vec{\mathcal{F}}$ (Figure 1.4a). Newton's law relates $\vec{\mathcal{F}}$ to the acceleration,

$$\vec{\mathcal{F}} = M\frac{d\vec{\mathcal{V}}}{dt}. \tag{1.11}$$

Multiplying by $d\vec{x}$, and using $d\vec{x} = \vec{\mathcal{V}}dt$, we have

$$đW = \vec{\mathcal{F}} \cdot d\vec{x} = M\frac{d\vec{\mathcal{V}}}{dt} \cdot d\vec{x} = M\frac{d\vec{\mathcal{V}}}{dt} \cdot \vec{\mathcal{V}}dt$$
$$= M\vec{\mathcal{V}} \cdot d\vec{\mathcal{V}} = d\left(\frac{1}{2}M\mathcal{V}^2\right),$$

which we interpret as an *energy balance* (Figure 1.4b),

$$\underbrace{đW}_{\text{energy input as work}} = \underbrace{d\left(\frac{1}{2}M\mathcal{V}^2\right)}_{\text{accumulation of kinetic energy}}. \tag{1.12}$$

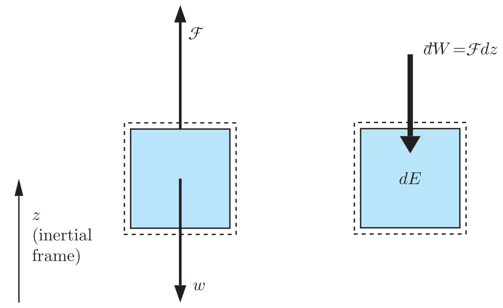
We therefore *define* the kinetic energy E_k of a mass M moving at velocity $\mathcal{V}$ relative to the observer as

$$E_k \equiv \frac{1}{2}M\mathcal{V}^2. \tag{1.13}$$

Note that in this case $đW = dE_k$ because there are no other energy changes or transfers to balance $đW$; $đW$ is always an inexact differential, but in this case it turns out to be balanced by the exact differential dE_k.

Potential energy

Next, consider a weight hanging from a rope in the Earth's gravitational field (Figure 1.5a). If we slowly raise the object by pulling on the rope, and neglect the slight extra force required to accelerate the mass, then $\mathcal{F} = Mg$. If we treat g as constant, then the work done by the rope on the object when we increase its elevation by an infinitesimal amount dz is



(a) Raising a weight increases its potential energy.

(b) Terms in the energy balance.

Figure 1.5 Potential energy balance.

$$đW = Mg\,dz = d(Mgz),$$

which we interpret as an energy balance (Figure 1.5b),

$$\underbrace{đW}_{\text{energy input as work}} = \underbrace{d(Mgz)}_{\text{accumulation of potential energy}}. \tag{1.14}$$

We therefore *define* the potential energy E_p of a mass M positioned a distance z above the (arbitrary) datum of the observer in a uniform gravitational field g as

$$E_p \equiv Mgz. \tag{1.15}$$

In this case $đW = dE_p$ because there are no other energy changes or transfers to balance $đW$; $đW$ is always an inexact differential, but in this case it turns out to be balanced by the exact differential dE_p. *Note that we do include the work done by the gravitational force in the energy balance as this is accounted for by the potential energy change.*

Power

The *rate* of energy transfer is called *power*. In this book we use an overdot to denote a rate of *transfer* (but never a rate of *change*). For example, dividing (1.14) by dt, a small increment in time over which the

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Table 1.1 SI mechanical units.

Primary quantity	SI unit	
Mass	kg (kilogram)	
Length	m (meter)	
Time	s (second)	
Secondary quantity	**SI units**	**Alias**
Velocity	m/s	
Acceleration	m/s^2	
Force	$kg \cdot m/s^2$	N (Newton)
Work, energy	$N \cdot m = kg \cdot m^2/s^2$	J (Joule)
Power	$J/s = kg \cdot m^2/s^3$	W (Watt)
Pressure	$N/m^2 = kg/\left(m \cdot s^2\right)$	Pa (Pascal)

change takes place, the energy balance of the system of Figure 1.5b, on a *rate basis*, is

$$\underbrace{\dot{W}}_{\substack{\text{rate of energy}\\ \text{input as work}}} = \underbrace{\frac{d(Mgz)}{dt}}_{\substack{\text{rate of accumulation}\\ \text{of potential energy}}}, \tag{1.16a}$$

where $\dot{W}$ denotes the *rate* of energy transfer as work,

$$\dot{W} \equiv \frac{đW}{dt}. \tag{1.16b}$$

Again we emphasize that $đW/dt$ is *not* the rate of *change* of W (this has no meaning), but is instead the rate of energy *transfer*.

1.6 Dimensions and Unit Systems

Eventually you will need numbers

In doing an analysis, it is a good idea to use symbols in order to keep the analysis general, and then insert specific numbers after the final equations have been developed symbolically. The quantitative results will be in the form of numerical values and units, and so engineers must be very comfortable working with numbers and various units of measure.

The SI unit system

This is a book for engineers of the future from all over the world, and for this reason we will work exclusively in the international standard system of units of measure known as SI (*Système Internationale*).

As for the USA, the transition to SI slowly began in the 1960s. SI is now the mandatory system for use in government laboratories, many technical journals, and a growing number of engineering firms (especially those that seek world markets). There are still vestiges of older measures which by the end of the twenty-first century are likely to be regarded as archaic. Probably by then we will no longer buy oil by the *barrel* (if there is any oil), or think of each barrel as containing about 6 million BTU (British Thermal Units) of energy. But the full conversion of US society to SI is likely to take at least another generation, so the modern engineer must be able to convert between these older measures and SI. This can be a very confusing task if one does not understand the basic ideas of units and dimensional systems. The purpose of this section is to help you develop this understanding.

Primary quantities

In any unit system there are a set of *primary quantities* for which one establishes some standards of measure. Table 1.1 lists the primary quantities and their units for the SI system. Note that the SI uses *mass, length,*

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William C. Reynolds , Piero Colonna
Excerpt
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and time as the primary mechanical quantities and hence is called an M-L-T system. The kg (kilogram), m (meter), and s (second) are the fundamental SI units of measure. Other SI primary quantities and corresponding units are: absolute temperature (Kelvin), electric current (Ampere), and luminous intensity (candela).

Standards for the primary quantities

The basic SI units will someday all be defined in terms of atomic standards easily reproduced anywhere with great precision. This is very nearly the case as of this writing. Prior to 1960 the second was defined as 1/86 400 of a mean solar day; then the definition was changed to 1/31 556 925.9747 of the tropical year 1900. Neither of these standards is very accessible, and so in 1964 the second was redefined in terms of the radiation frequency of a particular cesium spectral line, a standard accessible anywhere. The meter was redefined in 1960 as 1 650 763.73 times the wavelength of the orange-red line in the spectrum of krypton 86. Then, in 1986 the meter was redefined as the distance traveled through a vacuum by light in 1/299 792 458 s. Only the kilogram is still defined in terms of a particular artifact, namely a block of metal that is carefully maintained in Sèvres, France; someday the kilogram will be defined in terms of something more easily reproducible elsewhere, quite probably the rest mass of an electron.

The SI mass unit

Note that the *kilo*gram is *one* SI mass unit, and the *gram* is actually *one-thousandth* of the basic SI mass unit (1 gram = 10^{-3} kg = 1 mkg).[2] To maintain consistency in the nomenclature adopted by the SI system, a name for the mass unit without any prefix would seem more appropriate. A better choice might have been gram for the current kilogram and milligram for the current gram. These changes are favored by the authors, but not yet accepted by the science and engineering community.

[2] The prefix "kilo" is derived from the ancient Greek word for "one thousand", *i.e.*, *κιλιοι* (pronounced "kee-lee-oh-ee"). The prefix milli- is derived from the Latin word "mille" (pronounce "meel-leh") which means "one thousand".

Secondary quantities

Secondary quantities are defined in terms of primary quantities. The dimensions of secondary quantities, such as velocity, acceleration, force, and pressure, are determined by their definitions, and their units are combinations of the primary units. For convenience, a particular combination of the primary units is sometimes given an alias. Table 1.1 lists some important secondary quantities, their SI units, and the common alias used for the unit combinations.

Role of Newton's law

Newton's law, which relates the force exerted on a particle to its acceleration and mass, plays a crucial role in all unit systems. In general, Newton's law can be written

$$\vec{\mathcal{F}} = k_N M \vec{a}, \tag{1.17}$$

where k_N is a constant that depends on the unit system (Newton's constant). In the SI system, force is treated as a secondary quantity, and k_N is chosen to be unity and dimensionless. Thus, in SI, Newton's law sets the scale for force and makes the units of force kg · m/s^2. This combination of primary units is given the *alias* Newton (N). It is rather appropriate that 1 N is about the weight of an apple... If you do not get the joke, Google it!

Non-uniqueness of SI

There is another physical law that relates force, mass, length, and time, namely the law for the gravitational attraction force between two point objects of mass M_1 and M_2, separated by a distance r,

$$\mathcal{F} = k_G \frac{M_1 M_2}{r^2}, \tag{1.18}$$

where k_G is the *universal gravitational constant*; in SI we have that $k_G = 6.67 \times 10^{-11}$ m^3/kg · s^2. It is pure chance that twentieth-century humans decided to make the constant in Newton's law unity when they set up the SI; they could have instead chosen

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