SI EDITION

Principles of ENGINEERING THERMODYNAMICS

2nd Edition

John R. Reisel

CONVERSION FACTORS

Area:

$1\ \text{m}^2 = 10^4\ \text{cm}^2 = 10^6\ \text{mm}^2$
$1\ \text{m}^2 = 10.764\ \text{ft}^2$
$1\ \text{ft}^2 = 144\ \text{in}^2$
$1\ \text{ft}^2 = 0.092903\ \text{m}^2$

Density:

$1\ \text{g/cm}^3 = 1000\ \text{kg/m}^3$
$1\ \text{g/cm}^3 = 62.428\ \text{lbm/ft}^3$
$1\ \text{lbm/ft}^3 = 16.018\ \text{kg/m}^3$

Energy:

1 J = 0.73756 ft-lbf
1 kJ = 737.56 ft-lbf
1 kJ = 0.9478 Btu
1 ft-lbf = 1.35582 J
1 Btu = 778.17 ft-lbf
1 Btu = 1.0551 kJ
1 kcal = 4.1868 kJ

Energy Transfer Rate:

1 W = 3.413 Btu/h
1 kW = 1.341 hp
1 Btu/h = 0.293 W
1 hp = 2545 Btu/h
1 hp = 550 ft-lbf/s
1 hp = 0.7457 kW
1 ton of refrigeration = 200 Btu/min
1 ton of refrigeration = 211 kJ/min

Force:

$1\ \text{N} = 1\ \text{kg-m/s}^2$
1 N = 0.22481 lbf
1 lbf = 4.4482 N

Length:

1 cm = 0.3937 in.
1 in. = 2.54 cm
1 m = 3.2808 ft
1 ft = 0.3048 m
1 mile = 1.6093 km
1 km = 0.62137 mile

Mass:

1 kg = 2.2046 lbm
1 lbm = 0.4536 kg

Pressure:

$1\ \text{Pa} = 1\ \text{N/m}^2$
$1\ \text{Pa} = 1.4504 \times 10^{-4}\ \text{lbf/in}^2$
1 atm = 101.325 kPa
1 bar = 100 kPa
$1\ \text{lbf/in}^2 = 6894.8\ \text{Pa}$

	1 lbf/in^2 = 144 lbf/ft^2
	1 atm = 14.696 lbf/in^2
Specific Energy:	1 kJ/kg = 0.42992 Btu/lbm
	1 Btu/lbm = 2.326 kJ/kg
Specific Heat:	1 kJ/kg·K = 0.238846 Btu/lbm·R
	1 kcal/kg·K = 1 Btu/lbm·R
	1 Btu/h·R = 4.1868 kJ/kg·K
Volume:	1 cm^3 = 0.061024 in^3
	1 m^3 = 35.315 ft^3
	1 L = 0.001 m^3
	1 in^3 = 16.387 cm^3
	1 ft^3 = 0.028317 m^3
	1 gal = 0.13368 ft^3
	1 gal = 0.0037854 m^3

COMMON CONSTANTS

Universal Ideal Gas Constant:	$\bar{R}$ = 8.314 kJ/kmol·K
	= 1545 ft-lbf/lbmol·R
	= 1.986 Btu/lbmol·R
Standard acceleration due to gravity:	g = 9.8067 m/s^2
	= 32.174 ft/s^2
Standard Atmospheric Pressure:	1 atm = 101.325 kPa
	= 14.696 lbf/in^2
	= 760 mm Hg = 29.92 in. Hg
EE Unit Conversion Constant:	g_c = 32.174 lbm-ft/(lbf-s^2)

Principles of Engineering Thermodynamics

Second Edition, SI Edition

John R. Reisel
University of Wisconsin – Milwaukee

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Principles of Engineering Thermodynamics,
Second Edition, SI Edition
John R. Reisel

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To my wife Jennifer, and my children Theresa and Thomas—may Thermodynamics continue to provide them with modern wonders.

Contents

Appendices

Preface to the SI Edition

This edition of *Principles of Engineering Thermodynamics* has been adapted to incorporate the International System of Units (*Le Système International d'Unités or* SI) throughout the book.

Le Système International d'Unités

The United States Customary System (USCS) of units uses FPS (foot–pound–second) units (also called English or Imperial units). This system is also referred to as the English Engineering (EE) system of units. SI units are primarily the units of the MKS (meter–kilogram–second) system. However, CGS (centimeter–gram–second) units are often accepted as SI units, especially in textbooks.

Using SI Units in this Book

In this book, we have used both MKS and CGS units. USCS (U.S. Customary Units) or FPS (foot-pound-second) units used in the U.S. Edition of the book have been converted to SI units throughout the text and problems. However, in case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, but it also encroaches upon the intellectual property of the source. Some data in figures, tables, and references, therefore, remain in FPS units. Chapters 1 and 2 in particular contain USCS and FPS units; these chapters introduce you to these systems of units and allow you to practice converting between the most common systems. For readers unfamiliar with the relationship between the USCS and the SI systems, a conversion table has been provided inside the front cover.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units just before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, readers may contact the appropriate government agencies or authorities in their regions.

Preface

Mission

Why should an engineering student want to study thermodynamics? The answers are all around you. Look at all of the devices that use energy—electric lights, automobiles, computers, smartphones, and so many more. Things that don't directly use energy likely were made by machines that do use energy. In today's world, energy is being used everywhere, and Thermodynamics is the study of energy. Engineers need to know how to use energy effectively. As such, the goal of this book is to prepare students to be practicing engineers with an intuitive understanding of how energy-related systems work and how the performance of such systems is affected by variations in its operational parameters.

While the basic principles and concepts of thermodynamics were developed well over 100 years ago, they are still being used today to analyze and explain how things work in the world. Thermodynamics makes all of today's technology possible, and will continue to power the development of new technology in the future. Therefore, engineers need to have a strong fundamental understanding of thermodynamics in order to continue to develop technology to improve the world.

This textbook is written with the philosophy that it is most important to prepare engineers to understand how to use thermodynamics in professional practice. Engineers must gain an intuitive understanding of how changes in a parameter of a system will impact the energy-related performance of a process. The approach taken in this book is to help students develop this understanding. Throughout the book, students will be asked to use modern computational tools of their choosing to quickly vary the parameters of a system so that they can recognize interactions between features in systems. A historical problem with learning thermodynamics is that it is often taught as a subject that involves only solving individual problems with tabulated property data. Students who learn thermodynamics in such a manner often end up as practicing engineers who do not recognize how various parameters may impact the energy consumption of a piece of equipment or a process. For example, an engineering student may learn in thermodynamics how to solve for the power required to operate an air compressor. However, as a working engineer they may not realize that the energy consumption can be reduced by compressing cold air rather than hot air. As a result, their company may continue to pull hot air from the interior of a factory into the compressor intake, rather than using cold exterior air in the winter, which would waste both energy and money. This book aims to correct this deficiency that has plagued thermodynamics education in the past by encouraging and directing the students to explore the relationships between system parameters.

Special Features of the Book

Emphasis on Computer-based Properties and Equation Solving Platforms

To aid in their understanding of energy relationships, students are strongly encouraged to develop computer-based models of devices, processes, and cycles, and to take advantage of the plethora of Internet-based programs and computer apps for rapidly finding thermodynamic data; these are things that practicing engineers do regularly. Students who are comfortable with a particular equation-solving platform are encouraged to use that platform for their equation development. Some platforms may directly connect into thermodynamic property data, making such platforms potentially easier to use for students already familiar with the platform. Alternatively, an external property-data program can be used to find values for the properties, and these values can be directly input into an equation-solving program. This approach allows students to spend more time focusing on thermodynamics and less time learning a new piece of software.

Parametric Analysis-Based Problems

In keeping with the goal of developing an intuitive understanding of how thermodynamic systems work, many examples and problems throughout the book guide students to perform parametric analyses. These problems are designed to isolate a particular quantity and allow the students to learn how variation of that quantity affects the rest of the system.

Streamlining of Thermodynamic Topics

Another philosophical difference behind this textbook is a streamlining of the material presented in this book in comparison to other thermodynamics books. The content of this book focuses on what is most important for most students to learn about thermodynamics as they strive to become practicing engineers. This is not to say that there are not many other important topics in the subject of thermodynamics. However, the author believes that these topics are more suited for a higher-level engineering thermodynamics course—primarily a course to be taken by students engaged in graduate studies in energy-related areas.

Course Organization

The content of this book is suitable for either a one-semester course or a two-semester course sequence for thermodynamics. For a one-semester course, it is suggested that the material covered be Chapters 1-6, and if time permits some coverage of basic cycles (such as the basic Rankine cycle or the Otto cycle in Chapter 7, or the vapor-compression refrigeration cycle in Chapter 8) may be included. A two-semester sequence would include the remainder of the material in Chapters 7-11 in the second semester of thermodynamics. This second course focuses on applying the basic principles covered in the first course in practical systems. Students who complete only the first course will have a strong understanding of the basic engineering principles of thermodynamics and have some knowledge of the interrelationship between parameters impacting thermodynamic systems. A student who completes two courses will have a much deeper understanding of the relationship between thermodynamics parameters and will be capable of applying thermodynamics in a wide variety of mechanical systems.

This book aims to make thermodynamics enjoyable for students and help them understand the importance of thermodynamics in today's world. Many of the problems facing the world today revolve around the use of energy. Through the use of this book, it is expected that many more engineers will be prepared and eager to help solve these energy-related problems by properly applying the classic concepts of thermodynamics.

New in the Second Edition

A key concept behind this book is to keep the amount of content in the textbook manageable for today's students. As such, many of the changes in the second edition involve editorial changes to the content, with the intent of these changes being to improve the pedagogy of the text.

A new feature found throughout the textbook is "Question for Thought/Discussion." The purpose of these questions is to act as a stimulus for students to think about topics related to Thermodynamics and engineering. The questions are often centered on non-technical concepts. By thinking about and discussing these questions, students will gain insights into how energy use impacts individuals and the world. This will help them understand how engineers may use this information as they design and build. Instructors can either ask students to think about these questions on their own, or they can have class discussions on the topics. An added benefit is that attention paid to these questions should help programs meet the ABET student outcomes.

To address their growing use in many internal combustion engines in hybrid vehicles, a section on the Atkinson and Miller cycles has been added to Chapter 7. While the analysis of these cycles is not tremendously different from more traditional engine cycles, this section will draw attention to the evolving nature of engine design.

Finally, over 100 new end-of-chapter problems have been added to the textbook, offering up a new array of exercises through which students can learn thermodynamics.

Supplements for the Instructor

Supplements to the text include a Solution and Answer Guide that provides complete solutions to the end-of-chapter problems, Lecture Note PowerPoint™ slides, and an image library of all figures in the book. These can be found on the password-protected Instructor's Resources website for the book at login.cengage.com.

Acknowledgments

I would like to acknowledge the helpful comments and suggestions of the many reviewers of this book as it underwent development, including

- Edward E. Anderson, *Texas Tech University*
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- Dominic Groulx, *Dalhousie University*
- Fouad M. Khoury, *University of Houston*
- Kevin H. Macfarlan, *John Brown University*
- Kunal Mitra, *Florida Institute of Technology*
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- Chaya Rapp, *Yeshiva University*
- Francisco Ruiz, *Illinois Institute of Technology*
- David Sawyers, *Ohio Northern University*
- Keith Strevett, *University of Oklahoma*
- Victor Taveras, *West Kentucky Community and Technical College*

Their work has helped immensely in improving this book.

I also wish to thank those who taught me thermodynamics, including Charles Marston at Villanova University and Normand Laurendeau at Purdue University. Without their outstanding abilities to teach thermodynamics, I may never have developed the passion I have for thermodynamics. I also would like to acknowledge my colleagues, both at the University of Wisconsin—Milwaukee and elsewhere, for their thoughtful discussions on thermodynamics education over the years, which helped to form my perspective on how thermodynamics should be taught. This perspective has reached fruition in this book. The students whom I have taught over the years also deserve recognition for their patience as I've experimented with different pedagogical approaches.

Finally, I would like to thank all the individuals at Cengage who have been instrumental in the creation of this book. In particular, I would like to thank Timothy Anderson, Senior Product Manager; MariCarmen Constable, Learning Designer; Alexander Sham, Associate Content Manager; and Anna Goulart, Senior Product Assistant. Special thanks are also due to Rose Kernan of RPK Editorial Services, Inc. Their assistance has been invaluable in bringing this project to completion.

John R. Reisel

About the Author

John R. Reisel is a Professor in the Mechanical Engineering Department at the University of Wisconsin—Milwaukee (UWM). He received his B.M.E., with a minor in Mathematics, from Villanova University, and his M.S. and Ph.D. in Mechanical Engineering from Purdue University. His areas of research interest include combustion, energy usage modeling, energy efficiency, fuel production, sustainable engineering, and engineering education. He has received numerous awards in engineering education, including the UWM Distinguished Undergraduate Teaching Award and the UWM College of Engineering and Applied Science Outstanding Teaching Award. He was also a recipient of the SAE Ralph R. Teetor Educational Award.

Dr. Reisel is a member of the American Society for Engineering Education (ASEE), the American Society of Mechanical Engineers (ASME), the Combustion Institute, the European Society for Engineering Education (SEFI), and the Society of Automotive Engineers (SAE). He has served as division chair of the Engineering and Public Policy Division of ASEE, and program chair of the Technological and Engineering Literacy/Philosophy of Engineering of ASEE. Dr. Reisel is a registered Professional Engineer in the state of Wisconsin.

Digital Resources

New Digital Solution for Your Engineering Classroom

WebAssign is a powerful digital solution designed by educators to enrich the engineering teaching and learning experience. With a robust computational engine at its core, WebAssign provides extensive content, instant assessment, and superior support.

WebAssign's powerful question editor allows engineering instructors to create their own questions or modify existing questions. Each question can use any combination of text, mathematical equations and formulas, sound, pictures, video, and interactive HTML elements. Numbers, words, phrases, graphics, and sound or video files can be randomized so that each student receives a different version of the same question.

In addition to common question types such as multiple choice, fill-in-the-blank, essay, and numerical, you can also incorporate robust answer entry palettes (mathPad, chemPad, calcPad, physPad, Graphing Tool) to input and grade symbolic expressions, equations, matrices, and chemical structures using powerful computer algebra systems.

WebAssign Offers Engineering Instructors the Following

- The ability to create and edit algorithmic and numerical exercises.
- The opportunity to generate randomized iterations of algorithmic and numerical exercises. When instructors assign numerical WebAssign homework exercises (engineering math exercises), the WebAssign program offers them the ability to generate and assign their students differing versions of the same engineering math exercise. The computational engine extends beyond and provides the luxury of solving for correct solutions/answers.
- The ability to create and customize numerical questions, allowing students to enter units, use a specific number of significant digits, use a specific number of decimal places, respond with a computed answer, or answer within a different tolerance value than the default.

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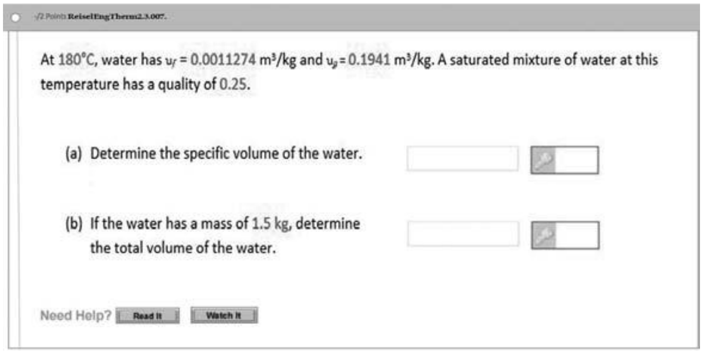
WebAssign Features for Students

Review Concepts at Point of Use

Within WebAssign, a "Read It" button at the bottom of each question links students to corresponding sections of the textbook, enabling access to the MindTap Reader at the precise moment of learning. A "Watch It" button allows a short video to play. These videos help students understand and review the problem they need to complete, enabling support at the precise moment of learning.



-/2 Points ReiselEngTherm2.3.007.

At 180°C, water has $v_f = 0.0011274\ \text{m}^3/\text{kg}$ and $v_g = 0.1941\ \text{m}^3/\text{kg}$. A saturated mixture of water at this temperature has a quality of 0.25.

(a) Determine the specific volume of the water.

(b) If the water has a mass of 1.5 kg, determine the total volume of the water.

My Class Insights

WebAssign's built-in study feature shows performance across course topics so that students can quickly identify which concepts they have mastered and which areas they may need to spend more time on.

Ask Your Teacher

This powerful feature enables students to contact their instructor with questions about a specific assignment or problem they are working on.

MindTap Reader

Available via WebAssign, **MindTap Reader** is Cengage's next-generation eBook for engineering students.

The MindTap Reader provides more than just text learning for the student. It offers a variety of tools to help our future engineers learn chapter concepts in a way that resonates with their workflow and learning styles.

Personalize their experience

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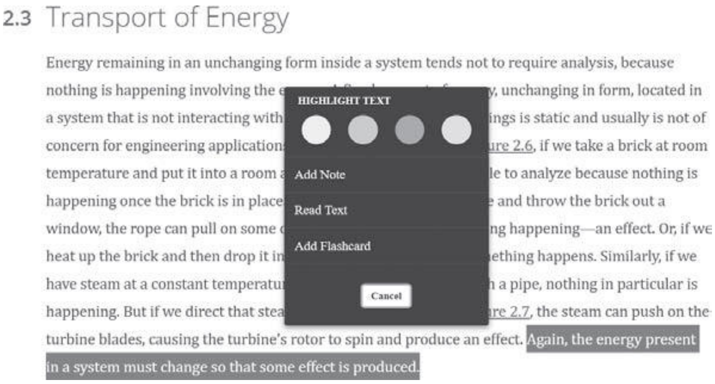
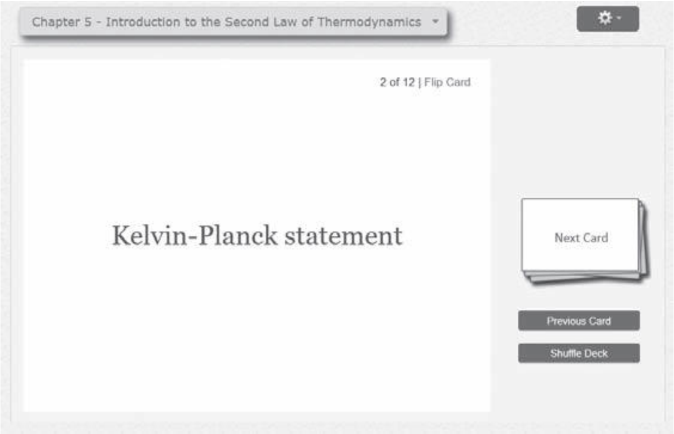


2.3 Transport of Energy

Energy remaining in an unchanging form inside a system tends not to require analysis, because
nothing is happening involving the e … y, unchanging in form, located in
a system that is not interacting with … ings is static and usually is not of
concern for engineering application … ure 2.6, if we take a brick at room
temperature and put it into a room … le to analyze because nothing is
happening once the brick is in place … and throw the brick out a
window, the rope can pull on some … ng happening—an effect. Or, if we
heat up the brick and then drop it in … ething happens. Similarly, if we
have steam at a constant temperatu … h a pipe, nothing in particular is
happening. But if we direct that stea … re 2.7, the steam can push on the
turbine blades, causing the turbine's rotor to spin and produce an effect. Again, the energy present
in a system must change so that some effect is produced.

Flexibility at their fingertips

With access to the book's internal glossary, students can personalize their study experience by creating and collating their own custom flashcards. The ReadSpeaker feature reads text aloud to students, so they can learn on the go—wherever they are.



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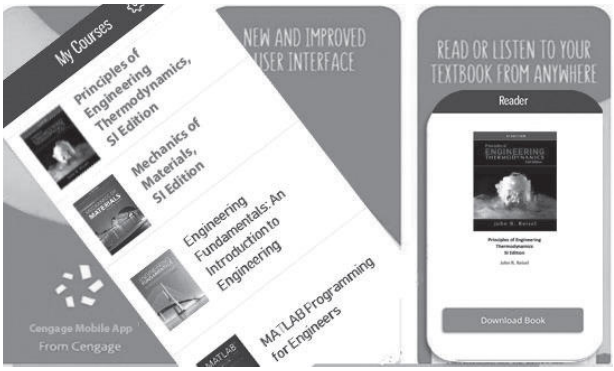

CHAPTER 1

Introduction to Thermodynamics and Energy

Learning Objectives

Upon completion of Chapter 1, you will be able to:

1.1 Describe what the subject of thermodynamics studies, and identify the types of engineering applications that involve thermodynamics;

1.2 Discuss concepts such as thermodynamic systems, processes, thermodynamic equilibrium, and properties;

1.3 Manipulate different temperature scales;

1.4 Recognize the difference between mass and force;

1.5 Use the basic properties of volume and pressure;

1.6 Explain and apply the Zeroth Law of Thermodynamics; and

1.7 Identify the different phases of matter.

Look around you. What do you see? You probably see people and things in motion, electrical devices in operation, and comfortable buildings. What you are seeing is energy being used. The use of energy is so commonplace that most people don't even notice it until it is unavailable, such as during an electrical power outage in a storm, or when an automobile runs out of fuel, or when someone is weak due to a lack of food. Anything that moves needs some energy to do so. Anything that is powered by electricity needs energy. Even the earth as a whole needs energy from the sun to stay warm and for life to flourish. The world as we know it exists because of energy in action.

If you have been even casually following the news in recent years, you have probably seen stories involving energy in the world. Stories on the rising costs and stressed supplies of petroleum or electricity are common. There are serious concerns over the effects on the environment caused by the rising levels of carbon dioxide (CO_2) in the atmosphere produced through the burning of fossil fuels. As people seek new, cleaner sources of energy, we see wind turbines rising across the world and solar panels appearing in locations that have rarely seen the use of such technology. The price and availability of energy, as well as how its use impacts the environment, is increasingly important to society.

Yet the demand that humans have for energy is at its greatest level ever. Not only are there more people than ever before, but people worldwide want the goods and standard of living associated with the wealthiest nations. People want ready access to transportation, and transportation systems require energy. People want buildings heated and cooled to the desired comfort level, and this requires energy. Factories use prodigious amounts of energy to produce the products that people want. Growing and transporting food requires energy. The demand for energy has never been higher, and it is likely to keep growing.

It can even be said that the harnessing of energy sources has been a key element in the development of civilization. **Figure 1.1** shows a number of examples of how the use of energy by people has developed over time. People learned how to control fire for heating and cooking. People harnessed the power of wind to pump water. Engines were developed to allow the chemical energy in a fuel to do useful work for us. Humans even learned how to unleash the power locked inside atoms to generate electricity. In the future, we don't know how humans will use the energy present in nature all around us, but it is likely that new means of harnessing energy will be needed to keep the development of civilization moving forward.

Engineers play a key role in creating systems that convert energy from one form to another, usually taking energy in a form that is otherwise rather useless and transforming

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FIGURE 1.1 Various images showing the application of energy by humans throughout history: a fire, a windmill, an automobile engine, and a nuclear power plant.

it so that people can use it to do something productive. For example, the energy bound up in the molecules that make up the fluid called "gasoline" is of little use as is. But if the gasoline is ignited with air in a combustion process, large amounts of heat can be released, and this heat can be used to create a high-temperature, high-pressure gas that can push on a piston in an engine, as shown in **Figure 1.2**; the work produced can be used to propel a vehicle forward. Engineers also play a key role in designing systems that use energy efficiently. Engineers can create devices that use less energy to accomplish the same task, and by using less energy these devices save consumers money. Furthermore, more efficient devices reduce the overall demand for more energy. For example, even a technology as widespread as lighting, illustrated in **Figure 1.3**, has seen dramatic improvements in energy efficiency. Light-emitting diode (LED) lights can be six times more efficient than incandescent bulbs and 40% more efficient than compact fluorescent lights, and last much longer than either technology. If engineers are to develop means of using energy efficiently while benefiting humankind significantly, they must understand the basic science behind energy.

Thermodynamics is the science of energy. If you look at the original Greek roots of the word, *thermos* means "heat" and *dynamikos* means "power"—and power applied to an object produces movement. Thermodynamics is the power of heat, or the movement of heat. As our understanding of energy has evolved, we recognize that energy involves more than just heat, and, as such, thermodynamics is considered the science of all energy. In engineering, we use thermodynamics to understand how energy is transformed from one form to another to accomplish a given purpose. Thus, we will be exploring not only the basic laws that describe thermodynamics but also the technology that is employed to accomplish tasks using energy.

FIGURE 1.2 A cutaway image of an internal-combustion engine cylinder.

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FIGURE 1.3 Examples of lighting technology: an incandescent light bulb, a compact fluorescent fixture, and an LED bulb.

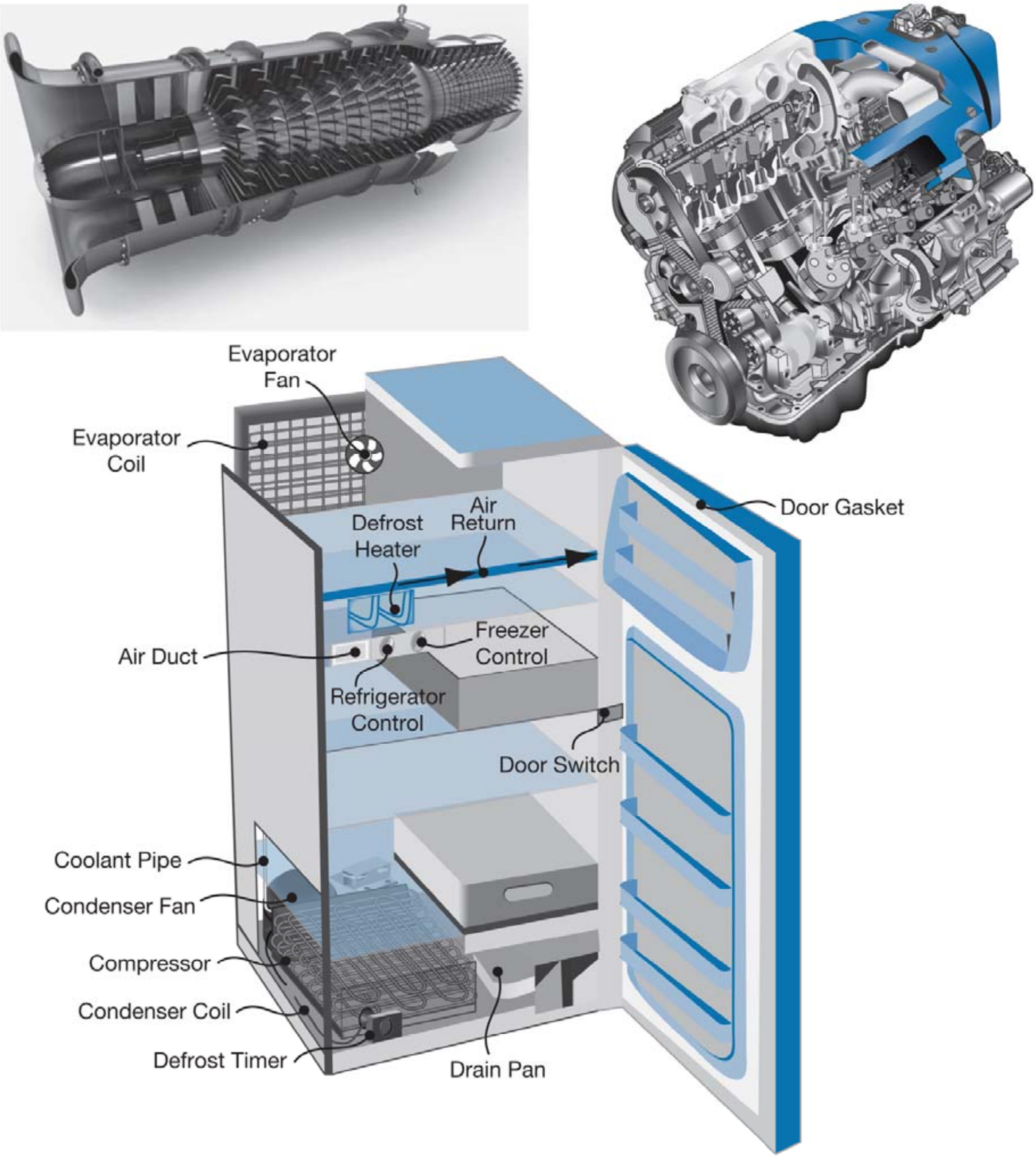

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FIGURE 1.4 Cutaway images of common energy-related technology: a gas turbine engine, a reciprocating engine, and a refrigerator.

Figure 1.4 shows many applications in the world today, developed by engineers, that use energy and for which thermodynamics is an integral design component. Turbines are used to transform the energy in a working fluid into a rotational motion of a shaft that in turn produces electricity in a generator. The turbines take in a high-energy gas or vapor (which generally has a high temperature and pressure) and extract energy from that fluid to produce the work needed to turn the shaft (also known as a rotor). A low-energy fluid is exhausted from the turbine. An automobile engine takes high-temperature, high-pressure gases (formed from the combustion of fuel in air, which releases the chemical energy bound up in the fuel) and has these gases push on a piston. The piston then drives the crankshaft, which transmits power to the wheels, thus moving the vehicle forward. Cooler, lower pressure gases exit from the cylinder after their energy had been extracted.

A refrigerator is used to keep food cool. It accomplishes this by taking electrical power and using this power to operate a compressor that increases the pressure of a vapor. Before the vapor is compressed, it is cooler than the interior of the refrigerator, and so it can remove heat from inside the refrigerator to cool the interior. After it is compressed, the vapor is hotter than the room temperature, and it is able to release the excess heat to the air outside the refrigerator. So, in this case, electrical power is used to change the state of the refrigerant so that it can accomplish the task of moving energy from a cooler space inside the refrigerator to a warmer space outside the refrigerator.

There are a vast number of devices and systems that are encountered every day that use thermodynamics to some extent, some of which are shown in **Figure 1.5**. A furnace to heat a building, an air conditioner to cool a building, the radiator on an engine, the sun heating the earth, a light bulb illuminating (and heating) a room, a bicycle being ridden, and a computer generating heat while performing its tasks are all such examples. All around you, energy is changing forms. Energy is moving throughout the world. Thermodynamics describes these energy motions and transformations. Although conventional thermodynamic analysis is not needed to analyze many things in everyday life, keep in mind that thermodynamics is fundamental to how the world functions.

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FIGURE 1.5 Examples of thermodynamics in the world today: an industrial furnace, the sun heating the earth, and human-powered bicycles.

Thermodynamics, and thermodynamic analysis, is defined by four scientific laws. These laws will be introduced when appropriate throughout the book. Scientific laws are not absolutely proven principles, but rather are concepts that are well established through observation and have never been shown to be incorrect. Occasionally, a law may need to be refined as our knowledge of the world deepens, but the basic principle usually remains unchanged. (For example, the law of the conservation of energy had to be modified to include mass for nuclear processes when Einstein showed that mass and energy were equivalent.) If one of the four laws upon which thermodynamics is based is ever shown to be incorrect, future scientists and engineers will need to reformulate the basics upon which thermodynamics rests. However, this is extremely unlikely.

Thermodynamics is one of the basic sciences that engineers use daily as they apply scientific principles to solve problems to aid humanity. This doesn't mean that every engineer will be performing thermodynamic analyses every day of his or her career, but some engineers do frequently design and analyze devices and processes by relying on the principles of thermodynamics. Others will only occasionally need to invoke thermodynamic principles in their careers. Still others rarely use thermodynamics directly, but thermodynamics still informs their work and may influence their work in ways that are not immediately apparent. As such, it is important for all engineers to be fluent in the basics of thermodynamics.

Before we can explore the principles of thermodynamics, we must first define and describe a number of basic concepts upon which our subsequent presentations will be based. This is the focus of the next section.

1.1 BASIC CONCEPTS: SYSTEMS, PROCESSES, AND PROPERTIES

1.1.1 The Thermodynamic System

At the basis of all thermodynamic analysis is a construct known as the ***thermodynamic system***. A thermodynamic system is the volume of space that contains the object(s) that are the focus of the thermodynamic analysis. The system is defined by the person performing the analysis and should be made as simple as possible. Unnecessary complexity should be avoided because it will either result in an incorrect analysis or will lead to significant amounts of additional work on the part of the person performing the analysis.

As shown in **Figure 1.6**, a thermodynamic system is delineated by a system boundary; everything inside the system boundary (which we will represent with a dashed line) is the system, and everything outside the boundary is considered the *surroundings*. **Figure 1.7** shows several possible systems that could all be considered the system for analyzing a particular problem. The quantity to be determined is the amount of heat needed to heat liquid water in a kettle on a stove. In Figure 1.7a, the system is proposed to be only the water in the kettle. In Figure 1.7b, the system is proposed to be the water and the kettle. In Figure 1.7c, the system is proposed to be the water, kettle, and the air above the water inside the pot. All three of these systems could be used to analyze the problem. However, the systems in (b) and (c) add complexity to the fundamental problem of determining the amount of heat that is added to the

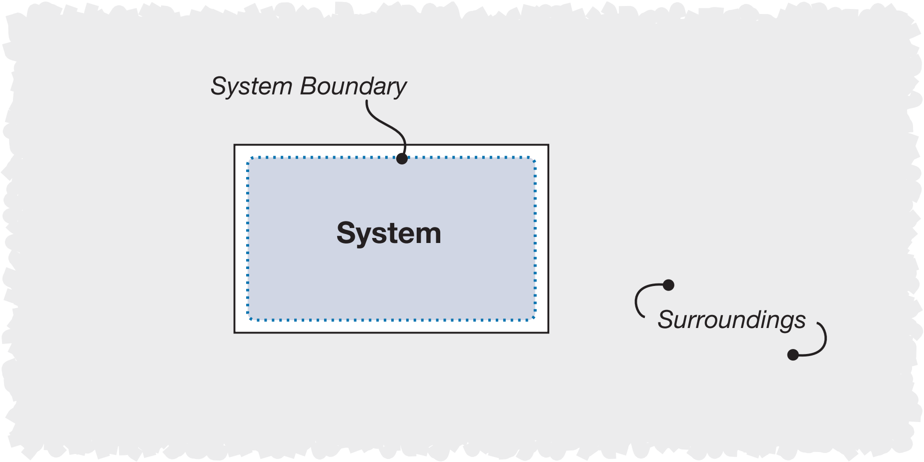

FIGURE 1.6 Example of a thermodynamic system, the system boundary (represented by a dashed line), and the surroundings.

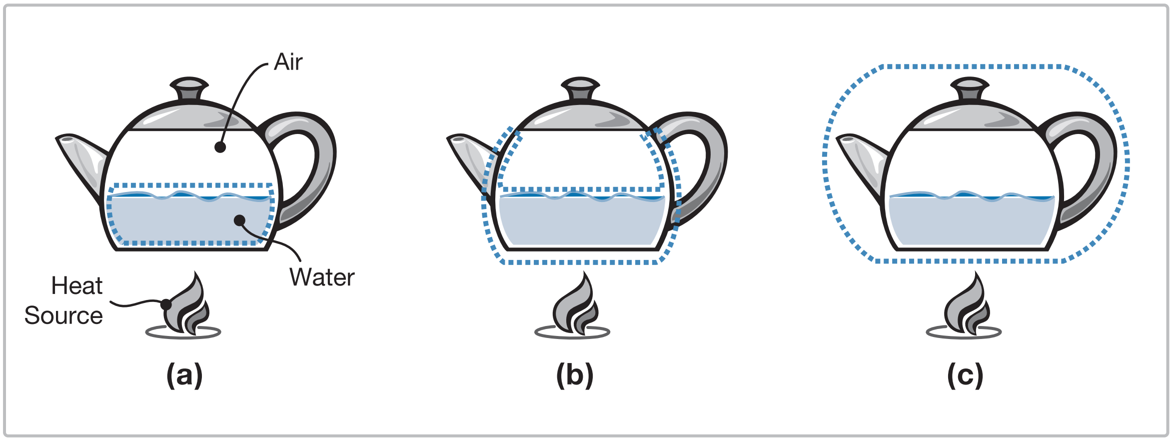

FIGURE 1.7 Examples of how the choice of the thermodynamic system changes the problem to be analyzed: (a) the system as only the water, (b) the system as the water and kettle, and (c) the system as the kettle, its contents, and its immediate surroundings.

water alone. In system (b), we would need to determine how much heat was added to both the water and the kettle, and then further analysis would be needed to determine how much heat was added to the water itself. In system (c), the problem would be further complicated by needing to determine how much heat was also added to the air, and then again separating out only the heat added to the water. So, although all three systems could be used for the problem, it is best to take care when defining the extent of the system so that the smallest volume possible is used in the analysis. This will reduce the amount of extra work that is necessary for finding the solution.

There are three types of systems; the types of systems are differentiated by whether or not mass and/or energy can cross the system boundary:

Isolated System: Neither mass nor energy can cross the system boundary.
Closed System: Energy can cross the system boundary, but mass cannot.
Open System: Both mass and energy can cross the system boundary.

Sometimes, a closed system is referred to as a “control mass,” whereas sometimes an open system is referred to as a “control volume.” However, in this book we will refer to each by the name of “closed” or “open” system, respectively.

In determining what type of system is to be employed for an analysis, we need to consider the important characteristics of the problem on the time scale likely to be employed. It is likely that given enough time, some small amount of mass may diffuse across the solid boundary of a closed system; however, if the amount of mass flowing across the system boundary is negligible over the time frame of the problem, it is likely best to view the system as a closed system. For example, if we have a bicycle tire filled with air, and the tire has no obvious leaks, it is safe to treat the system as a closed system if the time period under consideration is no more than a day or two. But if we are considering the tire over the course of a year, we may need to consider the impact of air very slowly leaving the tire—which would make it an open system.

Isolated systems will play a minor role in this book but are important in more advanced thermodynamics studies. One type of system that could be considered an isolated system is an insulated thermos bottle, after it has been closed, as shown in **Figure 1.8**. Suppose the bottle is filled with hot coffee at the start of the day. The bottle is closed, and then a short time later the bottle is opened and some coffee is poured out. The conditions of the coffee would change

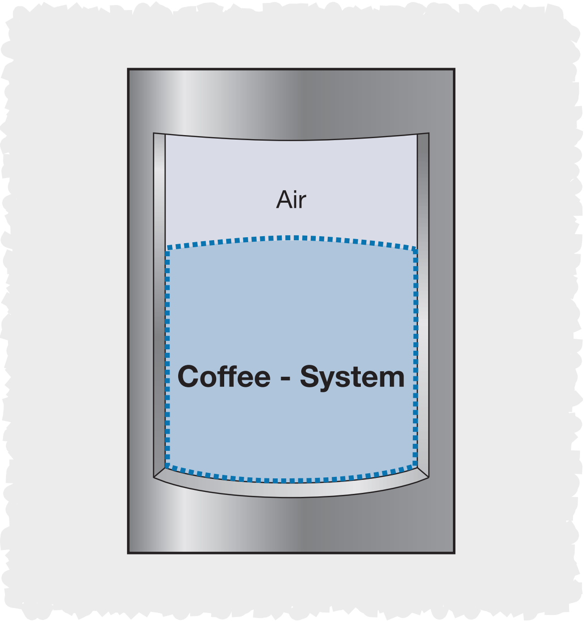

FIGURE 1.8 A cutaway diagram of an insulated bottle containing coffee and air, with the system being only the coffee.

little in that short time, and so between the time that the bottle was filled and the time when some coffee was poured out, the bottle could be considered an isolated system (as neither mass nor energy crossed the system boundary). The coffee would cool at a rate that is slow enough that the energy leaving the bottle could be ignored for relatively short periods of time. Although the choice of an isolated system may work well for a half hour or hour time duration, the system would probably be a poor choice for analyzing the coffee over the time period of a day. Over that longer period of time, the coffee will noticeably cool, and a closed system would be a better choice for modeling the system.

Another example of an isolated system is the entire universe, although performing a thermodynamic analysis of the entire universe is beyond the scope of this book. As far as we understand the universe, it contains all of the mass and energy that exists, and so mass and energy cannot cross the system boundary.

There are many more practical examples of closed systems, and some of these are shown in **Figure 1.9**. Solid objects generally are considered closed systems, unless they are specifically losing mass. A liquid or gas inside a closed container also is typically viewed as a closed system. The contents inside objects such as sealed

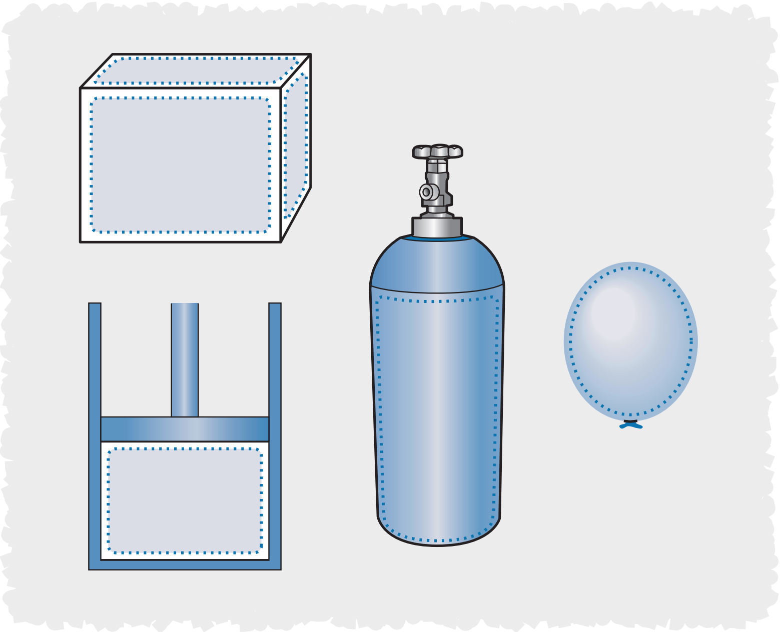

FIGURE 1.9 Examples of closed systems: a solid block of metal, the gas inside a tank, the air inside a balloon, and the gas in a piston–cylinder device.

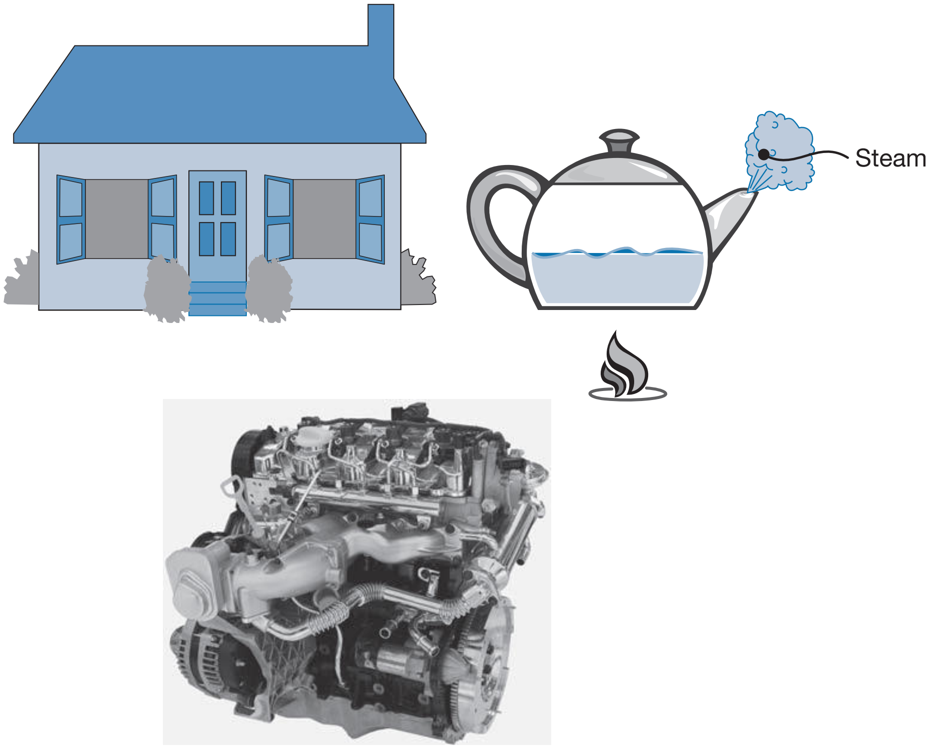

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FIGURE 1.10 Examples of open systems: a house with open windows, steam escaping from a kettle, and an automobile engine.

balloons are considered closed systems because, even though their volume changes, the mass inside the balloon doesn't change. Similarly, a piston–cylinder assembly containing a fixed mass of a gas or liquid will be considered a closed system.

Any system that clearly has mass being added to or removed from it is viewed as an open system. **Figure 1.10** provides a few of the many possible examples of open systems. A garden hose, a house with open windows, an air compressor, an automobile engine, and a kettle containing escaping boiling water are all examples of open systems. It should be noted that closed systems can be viewed as special applications of open systems. A thermodynamic analysis of a generic open system contains all the elements that would be seen in a closed system analysis; however, the closed system analysis will allow terms involving mass flow into and out of the system to be eliminated.

When determining the type of system to be used, it is important to consider the application of the object under consideration. For example, if we are in the act of filling or emptying a thermos bottle, we are dealing with what is clearly an open system rather than a potentially isolated system. Or, consider a kitchen refrigerator as shown in **Figure 1.11**. Assuming that the door is well sealed, the mass inside the refrigerator is fixed when the refrigerator door is closed. Energy in the form of electricity is still flowing into the refrigerator, and energy in the form of heat is being rejected to the environment as the refrigerant cools. (Heat is also slowly flowing through the walls to the interior of the refrigerator, but this heat can often be neglected for a well-built refrigerator.) Because energy can cross the system boundary but mass cannot, this would be viewed as a closed system. Now, consider if the door is open so that food can be

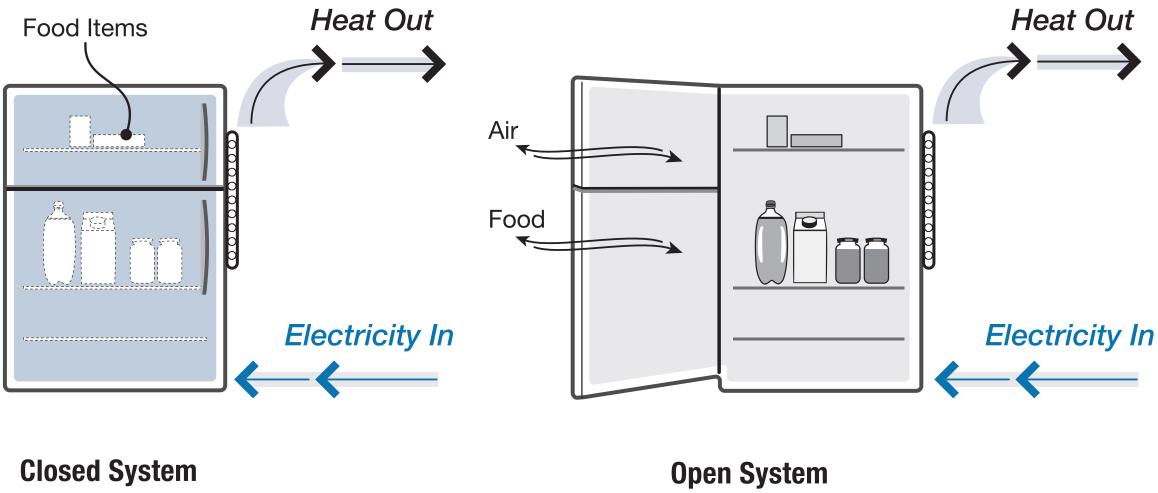

FIGURE 1.11 A refrigerator viewed as a closed system and as an open system.

added or removed from the refrigerator. Both air and the mass contained in the food can cross the system boundary; therefore, a refrigerator with an open door would be more appropriately viewed as an open system.

Alternatively, consider a piston–cylinder device inside an automobile engine, such as in **Figure 1.12**. When the intake and exhaust valves are closed, the mass trapped inside the cylinder is fixed, and the system is closed. But, if we open the exhaust valve, the gases inside the cylinder can flow out of the cylinder and into the exhaust manifold, making the piston–cylinder device an open system. Therefore, the choice of the type of system to use depends on the portion of the engine cycle under consideration.

Previously, we said that a garden hose is an open system. However, suppose that the valve that allows water to flow into the hose is shut. At this point, as long as the hose does not leak, there is a fixed mass of water that resides inside the hose. Some water may slowly evaporate, but because little mass if actively flowing into or out of the hose, the hose would be best considered a closed system. So, keep in mind that we cannot always determine whether a system is open or closed just by identifying the object under consideration, but rather we should also learn the nature of the process impacting the system.

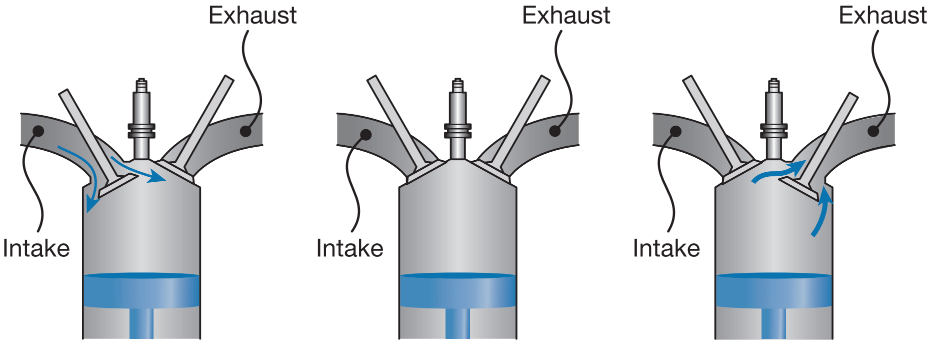

FIGURE 1.12 An engine cylinder as an open system (with intake valve open), as a closed system (with both valves closed), and as an open system (exhaust valve open).