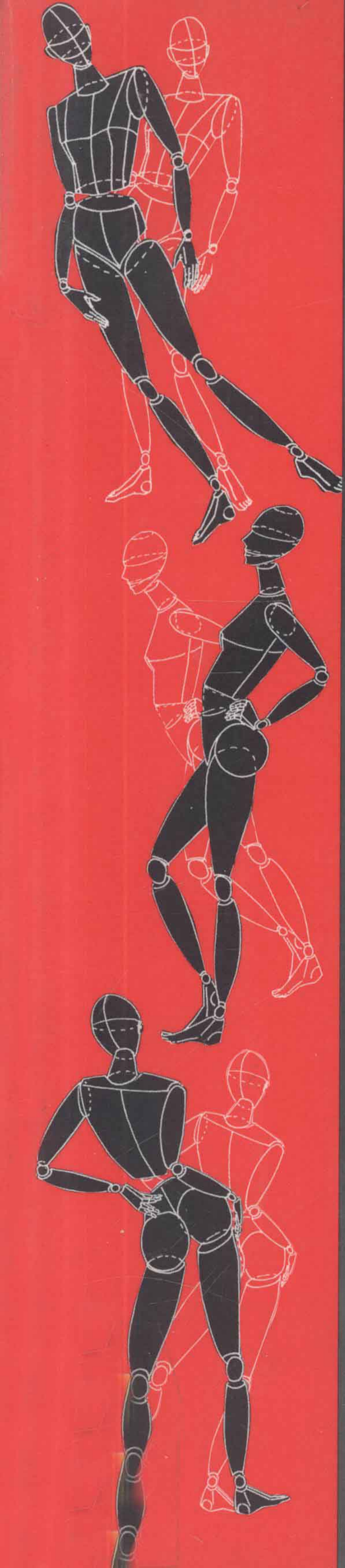

MECHANICS, HEAT, AND THE HUMAN BODY

An Introduction to Physics

Howard D. Goldick

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Prentice Hall

Library of Congress Cataloging-in-Publication Data
Goldick, Howard D.
Mechanics, heat, and the human body / Howard D. Goldick.
p.cm.
Includes bibliographical references and index.
ISBN 0-13-922816-0
1. Biophysics. 2. Physics. 3. Human mechanics. 4. Mechanics. 5. Heat. 6. Thermodynamics. I. Title.

QH505 .G63 2000
612'.014--dc21 00-044586

Publisher: Julie Alexander
Acquisitions Editor: Mark Cohen
Director of Production and Manufacturing: Bruce Johnson
Managing Production Editor: Patrick Walsh
Production Editor: Carol Eckhart, York Production Services
Production Liaison: Larry Hayden
Manufacturing Manager: Tiffany Price
Creative Director: Marianne Frasco
Cover Design Coordinator: Maria Guglielmo
Director of Marketing: Leslie Cavaliere
Marketing Coordinator: Cindy Frederick
Editorial Assistant: Melissa Kerian
Composition: York Production Services
Printing and Binding: R.R. Donnelley

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall Singapore Pte. Ltd.
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Photography and Artwork Credits:

Fishbane PM, Gasiorowicz S, Thornton ST, *Physics for Scientists and Engineers*, 2nd ed, 1996, Prentice-Hall, (f 1.3) 8, (f 1.8) 25, (f 1.61) 75, (f 2.1A) 90, (f 2.2) 91, (f 2.7) 97, (f 2.33) 118, (f 3.7) 162, (f 3.8) 162. • **Martini, FH, Timmons, MJ, *Human Anatomy*, 2nd ed, 1997, Prentice-Hall**, (f 1.4) 11, (f 1.29) 39, (f 1.43A) 56, (f 3.17) 185, (A 2) 201, (A 3) 202. • **Giancoli DC, *Physics for Scientists and Engineers*, 3rd ed, 2000, Prentice-Hall**, (f 1.55) 69, (f 2.1B-C) 90, (f 3.9) 164, (f 3.10) 165. • **Discover Magazine, July 1995**, (f 3.4) 149.

Prentice Hall

10 9 8 7 6 5 4 3 2 1
ISBN 0-13 922816-0

ACKNOWLEDGMENTS

When I began writing the class notes on which this book is based, I had no idea that it would result in writing a textbook. Having no prior experience in writing a text, I needed a great deal of support and encouragement. In particular, I needed expressions of encouragement in what was a long, time-consuming effort. I want to thank the chairman of my department, Joel Kagan, for his initial and continuing encouragement and support. When I began to search for a publisher, I found that there was little or no interest in my concept of the text. Sandi Hakanson, who represents Prentice Hall, encouraged me to submit my book to Mark Cohen, Health Sciences Acquisitions Editor for Prentice Hall. He encouraged me to submit a proposal and then arranged a contract. His continuing encouragement and support made the completion of the text possible. There were several people who read the text and made extremely helpful comments. Nancy Beverly of Mercy College used a preliminary version in one of her classes. David Markowitz of the University of Connecticut read two drafts and gave me many detailed comments. Howard Goldberg of the University of Hartford also read the final draft and helped me to adjust my particular way of writing to a more widely accepted style. I wish to thank Scott Sechrest of the CYBEX Corporation and Robert B. Barnes of the Barnes Engineering Corporation for their encouragement and permission to use proprietary illustrations. Finally, I thankfully acknowledge the many students who worked with the early versions of the notes on which this book is based. Without their comments and suggestions, I would never have continued in this effort.

PREFACE

In writing this book, I had the goal of providing an introduction to physics for those students who are particularly interested in the human body. On the basis of my many years of teaching physics to premedical, physical therapy and occupational therapy students, I set these guidelines:

1. The text would cover a limited number of distinct physics topics rather than providing an encyclopedic survey of the field of physics.
2. These topics would be illustrated (examples and problems) with reference to specific functions and characteristics of the human body.
3. The material would be covered in greater depth than is typical of an introductory text. This provides an opportunity to demonstrate the roles that physics and mathematical analysis play in understanding the body.
4. The examples and problems would span a range from straightforward applications of basic physics principles to those requiring significant analysis.

My students have, during the past five years, used the notes on which the text is based as a stand-alone text for a one-semester course. Much of the present content is based on their questions, criticisms, and suggestions. For example:

1. The discussion of each topic is built around a series of steps on which the analysis is based.
2. Both the SI and USA (English) systems of units are used in the book. Although the SI system is the legal system in this country and is the most commonly used system in the sciences, it is not widely used outside of those fields. Therefore, most students are much more familiar with the USA system, and this familiarity is addressed by inclusion of the USA system.
3. The various tables indicate sources of the data in the bibliography.
4. Answers to all of the quantitative problems are included.

I strongly suggest that students who use this book do not limit their efforts to reading it. To derive the full benefits that I hope are present, it is necessary that during your reading, you fill in any gaps between equations. There should be no "magic," no material that seems to come from nowhere. Do as many problems as your time allows. In your analyses of these problems, follow the suggested procedures rather than using shortcuts. Each analysis should include the basic applicable physics principle and clearly show how it is used. The answers to all problems are given. Do not work from these answers backward to produce your analysis. Such an approach is self-defeating because you will not be given the answers on exams or if you enter a field in which you must carry out such analyses.

One last comment: This text is intended to be a physics book, not an anatomy or physiology text. The human body is extremely complex, and to deal with its functions at an introductory level, many simplifications have been made. Modeling is employed; for example, muscles are treated as if they are simple line forces. Nevertheless, the results of the analyses are illustrative of the body's functions.

I look forward to your comments and questions regarding the book. Please contact me via e-mail at goldick@mail.hartford.edu.

INTRODUCTION

Our understanding of the human body and the means by which we deal with maladies and injuries have undergone amazing changes during the last 100 years. Illnesses that had been viewed as the result of Divine Intervention are now viewed in terms of the effects of bacteria and/or viruses. Amputation was a common medical response to severe trauma to limbs but is now very rare. The field of prosthetics has advanced to such a degree that those who have lost limbs are no longer doomed to living a marginal life but may now lead so full a life that it is sometimes difficult to realize that they have such a handicap. In the past, a person who had suffered a spinal cord injury that resulted in loss of the use of his or her legs could look forward only to life in a wheelchair. A person suffering that injury today can reasonably hope to walk and even climb stairs. Whereas exploratory surgery was common in the past, it is now very rare, having been replaced by noninvasive means. These and many other medical advances testify to the central role that the physical sciences and technology play in our dealings with the human body.

In this text, we will deal with the application of certain aspects of physics (mechanics and heat) to the human body. We will answer questions such as the following:

1. If a 150-pound woman were standing while holding a 10-pound child, how much force would be acting to compressing her lower back? (About 109 pounds) She bends over to put the child down into a playpen. How much force is now compressing her lower back? (439 pounds) (See page 109.)
2. Why does a person who has injured his right hip lean toward his right when walking? Why should he use a cane on his left rather than his right side? (See pages 113-115.)
3. What is the average power output of a catcher while stopping a fastball? (5 hp) (See page 146.)
4. How many times would you have to curl an 11-pound weight to burn off the energy you take in by eating six chocolate chip cookies? (5000) (See page 171.)
5. You know that your body produces heat when you exercise. How does the rate at which your body produces heat compare to the rate at which a 100-watt light-bulb produces heat? Surprisingly, even when you are not exerting yourself, as

while lying still in bed, you are producing heat at a rate comparable to that of the lightbulb. (See page 148.)

6. Why does your body seems to produce and retain fat so easily, and why is it so difficult to lose the fat? (See page 150.)
7. What is the function of kneecaps? (See page 192.)
8. Why is your spinal column curved rather than straight? (See page 97.)
9. Why does a pregnant woman usually lean backward when standing? (See page 97.)
10. How is it possible for a cold-blooded animal such as a tuna or a shark to have an internal temperature that is higher than that of the cold water in which it swims? (See page 188.)

As we learn how to analyze these and many other situations, we will become familiar with concepts that are basic to physics, such as Newton's laws and conservation of energy. We will also learn about the anatomy and physiology of the human body; in particular, we will deal with the muscular-skeletal system, digestion, and temperature regulation systems.

Perhaps more important than this information, which can be found in many books, is the techniques of analysis and quantitative reasoning that we will develop. **In my opinion, it has been the application of these techniques that has made possible the amazing advances in medicine and health care in general that we enjoy today.**

Historical Background

Our efforts to understand or explain the world seem to be inherent. Evidence for this statement comes from such diverse areas of study as comparative mythology and child psychology. Just as a child repetitively asks "Why?" and seems never to be satisfied by the answers, so it was with our ancestors. Unfortunately, this attitude is not supported by contemporary culture and has been replaced by a sort of sophistication and noncritical collective agreement characterized by

"OK?"

"Sure."

Try to imagine a culture where the interchange would be

"OK?"

"No, explain it more clearly."

That is the culture that our studies will represent.

Our studies will deal with the human body. How do we come to understand the body? This has been a long and difficult process. As we shall see, there were many questions that we would consider to be perfectly legitimate but that were, for many hundreds of years, the province of religion rather than science. There are many obvious questions about the body that must have been raised recurrently since time immemorial. Such questions as

"Where do babies come from?"

"Why do people die?"

"How can I get rid of this cold?"

"How can I get rid of this headache?"

are ancient; many of them have only recently been answered, and some of them still do not have definitive answers.

I remember attending an exhibit of cave art at the Metropolitan Museum of Art in New York City several years ago. The exhibit consisted of artifacts and reproductions of drawings that had been found in caves in France and Spain. These represented the artistic accomplishments of people who lived approximately 40,000 years ago. As I examined the exhibit, I noticed that although there were many female fertility symbols—small statues of female figures emphasizing breasts, hips, and bellies—there were no male fertility symbols, that is, phallic symbols. I asked an attendant whether the exclusion had been purposeful and was directed to an animal's horn that had been decorated with drawings. Still curious about the relative abundance of female symbols and scarcity of male symbols, it came to me that perhaps these artifacts dated from before the time when people realized that the male had anything to do with making babies. The role of the female is obvious, but who could remember and associate with the birth an activity that had happened nine months earlier?

No wonder that conception and birth were viewed as mysterious events, playing a central role in mythology and religion. As with conception and birth, so too with disease and death. It seemed to early people that one could divide concerns about the body into two categories: those that were inherently mysterious, such as conception, death, and disease, and those that were directly observable and hence understandable, such as wounds. It became accepted that while the former were to be dealt with through religion and other spiritual—that is, nonphysical—means (see the Book of Job), the latter situations were amenable to human intervention, such as stopping bleeding and setting broken bones. This separation was widely accepted through the eighteenth century.

Today, most people accept the physical, as opposed to spiritual, bases of birth, death, and disease. This change has affected human perception to such a degree that when there is no quick, effective intervention for such maladies as the common cold and AIDS, some people find it easier to believe that there is a conspiracy rather than a lack of scientific knowledge. How did such a massive change in attitude come about?

The major transition seems to have occurred in Europe in the seventeenth and eighteenth centuries, during what has been called the Scientific Revolution. Before that time, the generally accepted way to find answers to questions about the world was to look in old books. These books were usually Latin translations of the works of people who had lived between 300 B.C. and A.D. 200 in the world associated with classical Greece and the Hellenistic period that followed it. During the Roman period, this knowledge was disseminated throughout the empire by traveling scholars and physicians. With the fall of the empire in the fifth century, the flow of information ceased, and the so-called Dark Ages in Europe began. The knowledge was not lost, however. Some books had been kept and studied in monasteries. Other Europeans became aware of these works while engaging in commercial contacts with the Islamic world and as a result of the Crusades.

Many of the books that had originally been written in Greek and Latin were translated into Arabic after the Islamic conquests (632–750) of the Hellenistic cities of Spain, North Africa, and the Middle East. There were several centers of translation in the Islamic world.

Chief among them were ninth century Baghdad, tenth century Cairo, and twelfth century Toledo in Spain. Among the works translated were those of Aristotle, Archimedes, Hippocrates, Galen, and Euclid. The Hellenistic tradition of study in the fields of medicine, physics, and mathematics was continued by the Moslems, and this accumulated knowledge gradually began to find its way back into Europe. Many more translations became available to scholars in Europe after the Christian conquest of Islamic Spain in 1492. The impact that these works had on Europeans cannot be overestimated. They were viewed as the works of the people who had built the cities of Rome, Athens, Constantinople, and Alexandria, all of which were far more impressive than the largest cities of Europe. Thus, they were taken as Truth and as the source of all true knowledge about the physical world.

Of the Greek and Hellenistic scholars mentioned above, Claudius Galen (c. 130–200) deserves our particular attention. About a hundred of his works became available to Europeans through the processes described above. He was born in Pergamum (a large Hellenistic city located in what is now Turkey) and studied medicine there and at other major centers of Hellenistic learning in Smyrna, Corinth, and Alexandria. He then returned to Pergamum, where he served as a surgeon to a school for gladiators. He later went to Rome, where he became the physician to Emperor Marcus Aurelius. During his lifetime, he wrote many books, not only describing his investigations in the field of medicine but also recording the beliefs of others. His writings on anatomy were partly based on his surgical experience with the gladiators and on his experiences while accompanying the emperor on campaigns against German tribes. However, most of his knowledge of anatomy was based on dissections that he carried out on Barbary apes. His writings on physiology were based on observations but also on the prevailing philosophical traditions of his times. He believed that the functions of the body were based on spirits that endow us with the abilities to grow (natural spirit), to move (vital spirit), and to think (animal spirit). These spirits were not religious, supernatural, or mystical but were derived from the air in the liver, the heart, and the brain, respectively. His use of the word "spirits" was similar to our use of the word when we refer to ammonia spirits or spirits of alcohol—more as a vapor than a ghost. Galen's work was taken as gospel by the physicians of the Middle Ages, not to be questioned or subjected to independent verification. This attitude began to diminish with the work of Andreas Vesalius (1515–1564).

His major work, *De Humani Corporis Fabrica* (*About the Workings of the Human Body*, usually referred to as *Fabrica*), published in 1543, did not merely repeat what Galen had written. Vesalius described what he had observed while doing dissection. However, he accepted the main ideas about physiology that Galen had propounded. His contributions to anatomy that clearly showed errors in the Galenic texts set the stage for continuing investigations.

In 1687, Isaac Newton published *Philosophiae Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*, usually referred to as the *Principia*). In this book, Newton argued that the physical world could be understood, not by reference to the old books but by the application of close observation and logical analysis employing mathematics. He demonstrated the usefulness of this approach by showing how he could explain the motions of the planets, the comets, and the moon and the cause of high and low tides. His work made a great impression on those who were trying to understand the world and were not satisfied with the old answers. Although Newton's work emphasized the fields that we would call physics and astronomy, his work also made an impact on medicine.

In 1702, Richard Mead, a physician, published *A Mathematical Account of Poisons.* The book began with the claim that the study of mathematics would show doctors how to solve the intractable problems of medicine. His contemporary, Giorgio Baglivi, professor of anatomy in Rome wrote (paraphrased), "the human body is truly nothing else but a complex of chemical-mechanical motions, depending on such principles as are purely mathematical. For whoever takes an attentive view of its fabric, he'll really meet with shears in the jaw-bones and teeth . . . a pair of bellows in the lungs, the power of a lever in the muscles, pulleys in the corners of the eyes, and so on." (Lenihan, 1975.) Later in the book, Baglivi wrote, "We must not be surprised to find that the true and genuine cause of diseases can never be found by theoretical philosophical principles."

Even with the appearance of such innovative works, the Galenic ideas relating disease to humors and spirits continued to be widely held. The removal of such spirits from a sick person by techniques such as blood letting and trepanning could be found well into the nineteenth century.

The idea that one could use physics and mathematics to better understand the body was wonderfully supported by the discovery of X-rays, announced by Professor W. C. Roentgen of the University of Wurzenberg in Germany in November 1895. The medical applications of this new phenomenon followed with amazing speed. The first medical X-ray in the United States was taken on February 3, 1896, by Professor Edwin Frost of Dartmouth. In March 1896, Dr. J. Daniels of Vanderbilt University announced that irradiation of a colleague's skull had resulted in hair loss. Removal of a hairy birthmark was reported in 1897 and of a skin tumor in 1899. The success of X-rays established the great utility of physics and mathematics in the efforts to understand the human body.

Since the turn of the twentieth century, the most commonly accepted mode of gaining understanding of the body has been characterized by the application of biology, chemistry, physics, and mathematics. The almost magical level of medical technology is built on these bases. We will now begin a detailed study of this process.

CONTENTS

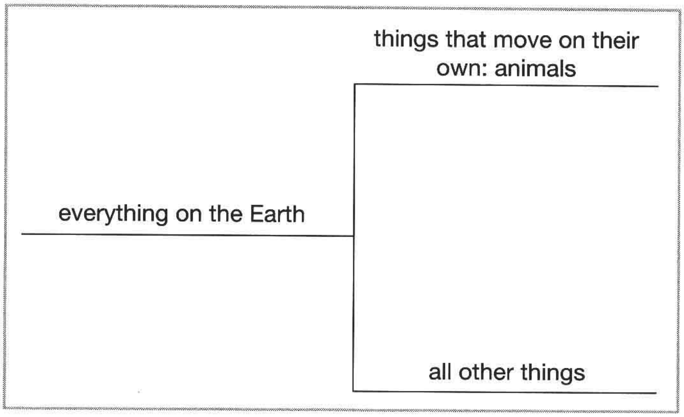
1

Linear Motion and Force

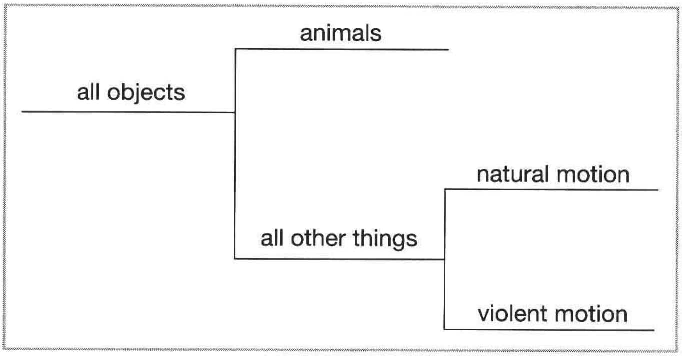
Motion

One of the most obvious characteristics of the body is that of motion. Not only did people wonder what makes the body move but they even debated the very nature of motion. One of the recurring topics in mythology and religion has been to explain the motion of the sun, the stars, and the moon. On a much more mundane level, it is easily noticed that some things in our environment move and some do not. Of those that do move, some move because something else (such as the wind) makes them move, while others move on their own. The things that move on their own are generally considered to be alive; we call them animals. Notice the similarity between the word "animal" and the words "animate" and "animation." These words come from a Greek word for breath, soul, or spirit. It came to mean "alive". Thus an animated picture is one that seems to be alive; it is a moving picture. We realize that plants are also alive, but since they do not move on their own, they are somehow considered less alive than are animals. Other things, such as rocks, do not move unless something makes them move, and they are clearly not alive. So we can consider two categories: things such as animals that can move on their own and all other things.

One of the earliest writers on this subject was Aristotle (384–322 B.C.). The effort to understand motion played a major role in his analysis of the physical world. He wrote that each inanimate (nonanimal) object has a natural, or inherent, motion that is either straight



up or straight down, depending on the major constituent component of the object. The four basic substances of which everything is composed were fire, air, water and earth. (*Note*: The capitalized terms are used to distinguish between normal fire, air, water, and earth and the Aristotelian substances of which normal materials are formed.) According to Aristotle, the natural motion of fire and of air is straight up, and that of water, and of earth is straight down. Natural motion was inherent in the object, thus not requiring any external agent. An object that displayed any motion other than its natural motion was said to be exhibiting unnatural or violent motion. **If an object is observed to be moving in a direction that is not consistent with its natural motion then an external agent or force must be at work causing the unnatural or violent motion.**



For example, if a rock is seen to be moving straight down, it is not surprising because the rock is made of earth and so its natural motion is straight down. But if the rock were observed to be moving up or horizontally, then there must be some force or external agent acting on the rock, causing it to move with the observed unnatural motion. Maybe the rock is in someone's hand, or maybe a very strong wind is blowing. When water mixes with air (evaporation) or comes out of a fountain, it goes up, but this is not the natural motion of water. Eventually, its natural motion must take over, and it falls (rain). If embers or dust rise because they are affected by hot air from a fire, they will eventually fall back because of their natural motion.

Since most of the motion that we observe going on around us is neither straight up nor straight down, it may be said that most motion is caused by external forces. This concept was generally accepted from the fourth century B.C. until the early seventeenth century, when Galileo Galilei (1564–1642) successfully challenged it.

Galileo's two major works were the books *Dialogue Concerning the Two Chief World Systems (1632) and Discourses and Mathematical Demonstrations Concerning Two New Sciences Pertaining to Mechanics and Local Motions* (1638). In the *Dialogue,* Galileo contrasted the accepted Ptolemaic model of the universe (the earth is the center of the universe) with the more recently developed Copernican model (The sun is the center of the universe). He strongly and very effectively supported the latter. In the *Discourses,* he attacked the analysis of the world as carried out by the Aristotelians. It was in this work that Galileo dealt with motion.

Although Galileo's works referred to physics and astronomy, his main goal was to introduce a new way (actually a rebirth of the Hellenistic approach exemplified by Archimedes, Aristarchus, etc.) of dealing with the world. This new way was based on observation and reason rather than appeal to authority and tradition. His writings were very important in the spread of this new way of coming to understand the world, for two reasons. He wrote in Italian rather than Latin, and he wrote in the form of readable dialogues—conversations rather than scholarly texts. Both of these contributed to a new phenomenon: Scholarly books became available to literate nonscholars who could read Italian but not Latin. Before Galileo's books, scholarly texts were readable only by those who could read Latin and who had the training to appreciate the complex arguments—in effect, only those who were associated with the Church or with the universities. Galileo was trying to reach an entirely different audience, literate people who were not part of the scholarly class.

Perhaps the following section will demonstrate how Galileo used the dialogue technique in advancing his philosophy. Three characters are involved in the *Discourses*: Salviati (representing Galileo), Simplicius (representing the Aristotelians), and Sagredo (a disinterested, intellectually curious bystander). Salviati and Simplicius argue, each trying to convince Sagredo that he is right and the other is wrong. In one of the episodes, Galileo attacks the concept of natural motion. The following exchange (paraphrased) is found:

SALVIATI: Please describe the motion of a moving box-shaped object that is free of external forces.

SIMPLICIUS: If the object is not supported on a surface, then it will fall straight down, because it is composed of Earth.

SAL.: Suppose that it is on a surface?

SIMP.: If the object is sliding down along the surface, it will continue to slide down, going faster and faster because it is composed of Earth and its natural motion is down. If the object were sliding up along the surface, it will gradually slow down, eventually come to a stop, and then slide back down as described before, again because of its natural motion down.

SAL.: Suppose that the surface is such that the object is neither sliding up nor down, but remains the same distance from the earth?

SIMP.: The object will slide, slow down, and gradually come to a stop because of friction between the surfaces.

SAL.: Suppose that the surfaces are carefully polished?

SIMP.: Then the object will slide farther before it slows down and stops.

SAL.: And if the two surfaces are made as smooth as possible and perhaps some fine oil is placed on the surfaces?

SIMP.: Then the object will slide even farther.

SAL.: As the surfaces were polished, frictional forces were reduced. As the surfaces were polished even more and as they were lubricated with fine oil, friction was reduced to almost zero. Therefore the external agent has been reduced, and yet the motion continued. **Here is an example of motion that does not require an external agent and yet is clearly not natural motion, that is, it is not either up or down.**

Here, Galileo argued very persuasively that force does not cause motion. As we shall see later, he advanced the idea that force causes motion to change. Thus, if an object speeds up, slows down, or changes direction, its motion changes, and it must be that a force was acting on it to cause the change. If there is no force acting on an object or if all of the forces that are acting on it happen to cancel, the motion should not change. This idea was later explicitly expressed as **Newton's first law:**

If the total force acting on an object is zero, then that object will exhibit constant motion. This means that if it is at rest, it will remain at rest. If it is moving, it will continue to move at constant speed, in a straight line.

EXAMPLE 1.1

Consider a car that is driving on an icy road. Let us assume that, because of the ice, there is no friction. The driver may attempt to stop the car by applying the brakes. However, Newton's first law can be applied to explain what will happen. The force of gravity (the weight of the car) acting on the car will be balanced by the force of the road pushing up on the car. We have already noted that there is no friction. Therefore, there is no net force acting on the car so the motion of the car will remain constant. Even though the driver applies the brakes and hence stops the wheels from turning, the car will continue at the same speed, sliding along the road. If the driver were to turn the steering wheel, attempting to steer, the car would still continue on a straight-line path. It is important to understand that forces associated with the brakes of a car or a steering wheel represent *internal forces*, **forces within the car.** For the motion of the car to change, it is necessary that external forces play a role. If there are no external forces or if they cancel (the net force then being zero), the motion of the object will be constant. It will travel at a constant speed in a straight line.

Galileo also argued that motion itself was ambiguous. He maintained that motion is relative, not absolute. Whether something is moving or which way it is moving depends on the motion of the observer. (This concept was generalized almost 300 years later by Albert Einstein (1879–1955) in his special theory of relativity). Therefore, motion should not be taken as a basic quantity on which an understanding of the world would be based.