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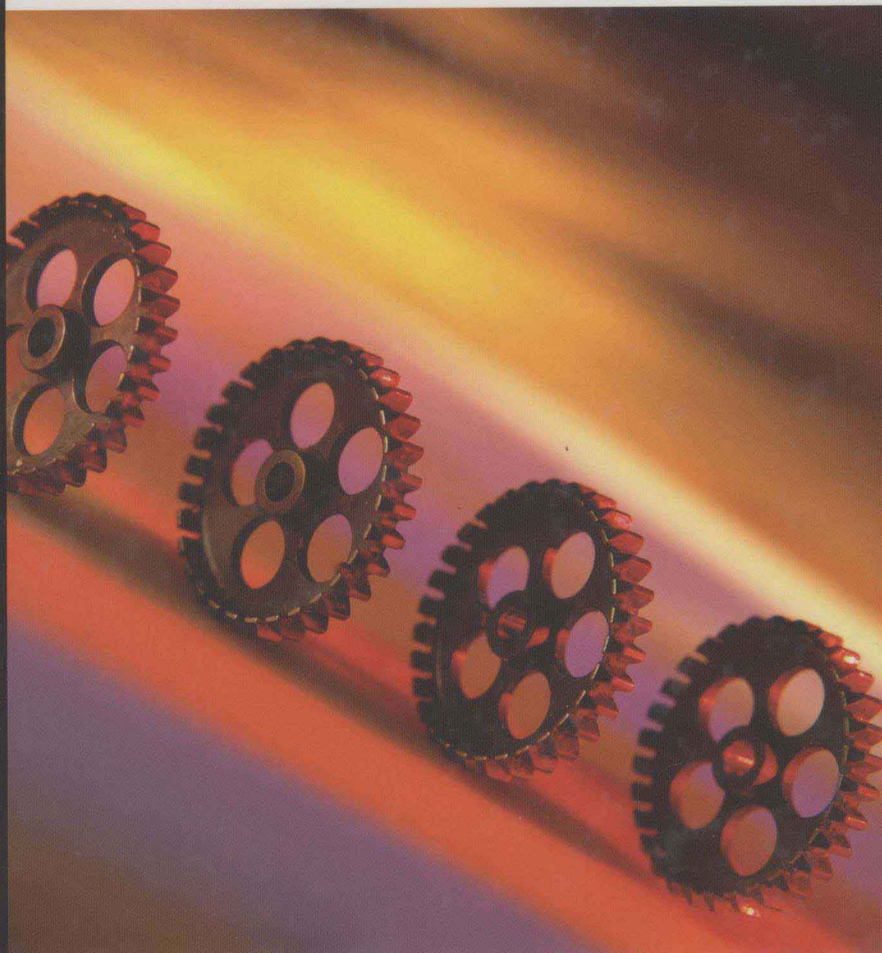
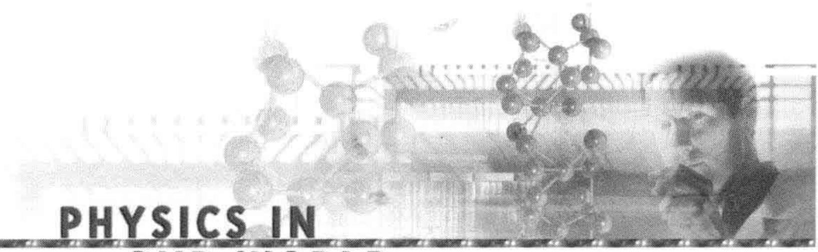
PHYSICS IN OUR WORLD

# FORCE AND MOTION

KYLE KIRKLAND, PH.D.





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# FORCE and MOTION

*This book is dedicated to Dr. Jesse L. Kirkland (1931–2006), who applied his knowledge of physics and engineering mechanics while working for NASA and the Department of Defense. To my regret, he was a man and father I never really knew.*

# PREFACE

THE NUCLEAR BOMBS that ended World War II in 1945 were a convincing and frightening demonstration of the power of physics. A product of some of the best scientific minds in the world, the nuclear explosions devastated the Japanese cities of Hiroshima and Nagasaki, forcing Japan into an unconditional surrender. But even though the atomic bomb was the most dramatic example, physics and physicists made their presence felt throughout World War II. From dam-breaking bombs that skipped along the water to submerged mines that exploded when they magnetically sensed the presence of a ship's hull, the war was as much a scientific struggle as anything else.

World War II convinced everyone, including skeptical military leaders, that physics is an essential science. Yet the reach of this subject extends far beyond military applications. The principles of physics affect every part of the world and touch on all aspects of people's lives. Hurricanes, lightning, automobile engines, eyeglasses, skyscrapers, footballs, and even the way people walk and run must follow the dictates of scientific laws.

The relevance of physics in everyday life has often been overshadowed by topics such as nuclear weapons or the latest theories of how the universe began. Physics in Our World is a set of volumes that aims to explore the whole spectrum of applications, describing how physics influences technology and society, as well as helping people understand the nature and behavior of the universe and all its many interacting parts. The set covers the major branches of physics and includes the following titles:

- *Force and Motion*
- *Electricity and Magnetism*

- *Time and Thermodynamics*
- *Light and Optics*
- *Atoms and Materials*
- *Particles and the Universe*

Each volume explains the basic concepts of the subject and then discusses a variety of applications in which these concepts apply. Although physics is a mathematical subject, the focus of these books is on the ideas rather than the mathematics. Only simple equations are included. The reader does not need any special knowledge of mathematics, although an understanding of elementary algebra would be helpful in a few cases. The number of possible topics for each volume is practically limitless, but there is only room for a sample; regrettably, interesting applications had to be omitted. But each volume in the set explores a wide range of material, and all volumes contain a further reading and Web sites section that lists a selection of books and Web sites for continued exploration. This selection is also only a sample, offering suggestions of the many exploration opportunities available.

I was once at a conference in which a young student asked a group of professors whether he needed the latest edition of a physics textbook. One professor replied no, because the principles of physics "have not changed in years." This is true for the most part, but it is a testament to the power of physics. Another testament to physics is the astounding number of applications relying on these principles—and these applications continue to expand and change at an exceptionally rapid pace. Steam engines have yielded to the powerful internal combustion engines of race cars and fighter jets, and telephone wires are in the process of yielding to fiber optics, satellite communication, and cell phones. The goal of these books is to encourage the reader to see the relevance of physics in all directions and in every endeavor, at the present time as well as in the past and in the years to come.

# ACKNOWLEDGMENTS

THANKS GO TO my teachers, many of whom did their best to put up with me and my undisciplined ways. Special thanks go to Drs. George Gerstein, Larry Palmer, and Stanley Schmidt for helping me find my way when I got lost. I also much appreciate the contributions of Jodie Rhodes, who helped launch this project; executive editor Frank K. Darmstadt and the editorial and production teams who pushed it along; and the many scientists, educators, and writers who provided some of their time and insight. Thanks most of all go to Elizabeth Kirkland, a super mom with extraordinary powers and a gift for using them wisely.

# INTRODUCTION

*FORCES* COME IN all quantities, from barely noticeable to practically irresistible. A single molecule of air glancing off a person's skin exerts an ignorable force, but together air molecules exert a *pressure,* called atmospheric pressure, which is important in nearly everything people do. And when the wind starts to blow faster than a car on an interstate highway, as it does during a hurricane, forces can reach catastrophic levels.

Forces cause motion, and the study of force and motion is a branch of physics known as mechanics. Motion and force are particularly important in today's mobile society and economy for many reasons. Ships, airplanes, and freight trains haul cargo over long distances; workers commute to and from the office in automobiles or passenger trains; students commute to and from school in buses and automobiles, on bicycles, or by the old-fashioned way of putting one foot in front of the other.

Almost everything moves, and motion can take several forms. An object can move in a straight line, follow a curved pathway, spin around its axis, move back and forth in a periodic way, or make some combination of these movements. Most moving objects on Earth travel through either air or water—substances that have tremendous effects on a pitcher's curveball, a sailor's boat, a diver's submersible, and almost everything else, though often in a less obvious manner than in these examples. Efficiency is important—otherwise transportation would waste precious resources—and safety is even more important. Physics has a lot of principles that apply to both.

*Force and Motion* looks at forces and motions and how physics, through simple and general concepts, affects the way people live and how the world around them works. No matter what form a movement takes, forces govern the motion. Some of these forces, such as the collision that sends a baseball flying away from a bat, are easy to observe; other forces, such as the one that gives a rocket its thrust, are more difficult to see. But all objects in motion obey laws, whether the object is a wheel or a baseball, a *tsunami* in the ocean or a person walking down the street. The same type of force also turns up in surprisingly distinct places—the force that keeps the space shuttle in its *orbit* is the same as that which gives a block of granite its *weight.*

Objects in motion have *energy.* So does a stretched rubber band or water in an elevated water tank, although this energy is different—it is stored, or potential energy. Storing up energy and converting it into motion is a common way of getting around, and doing this without using up all the world's energy or polluting the environment is another process in which physics is essential.

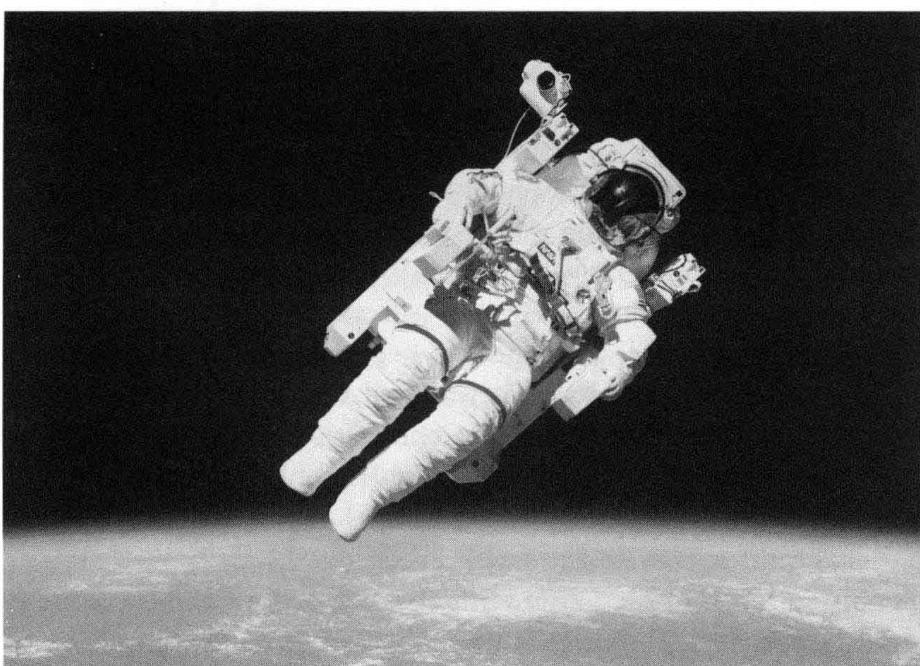
Each chapter of *Force and Motion* focuses on a single aspect of force and motion. Yet each aspect branches out, covering a wide range of phenomena and relating them in ways unimaginable without the science of physics.

# CONTENTS

# 1

# GRAVITY

AN ASTRONAUT FLOATING in space has no sense of up or down. On the surface of Earth, it is the steady downward tug of gravity that provides this sense. Animals and people are so adapted to gravity that this force seems to be a requirement for



Astronaut Bruce McCandless II performed this extravehicular activity in 1984. A backpack with nitrogen jet thrusters provided maneuverability. *(NASA)* good health: an astronaut's bones and muscles are often significantly weakened after a lengthy stay in orbit.

But gravity's reach extends well beyond the surface of the planet. Sometimes an orbiting astronaut is said to be weightless or in "zero gravity," though this is not accurate. Gravity is still present, although the downward sense of direction is not. Gravity can be subtle, and physicists did not understand this force for a long time. After all, the force that makes an apple fall to the ground on Earth would not necessarily seem to be the same force that holds the solar system together. People believed that the two were different for thousands of years until Sir Isaac Newton (1642–1727) discovered the *universal law of gravitation.*

Because the force of *gravitation* affects what happens not only on this planet but also everywhere else in the universe, it has a tremendous influence on the lives of people here on Earth and on those who venture beyond. Exploration of the solar system, which began in the 1950s, requires a knowledge of gravitational physics, and would not be possible without it. This chapter describes the many ways that the force of gravitation affects people here on Earth, as well as the people who are or will travel into space.

## Falling Down

Even before Newton's time, people knew they had to aim a little above a target when using a bow and arrow, or they would miss. The arrow does not follow a straight line to the target but instead curves slightly downward. Gravity affects all things, even swiftly moving arrows. Later, when people began to use even faster projectiles such as cannonballs, it was still necessary to correct for the downward pull of gravity. In the 20th century, as weapons became so powerful that shells could be lobbed for miles, military engineers formulated mathematical tables so that artillery officers could aim their guns with precision. These ballistic tables accounted for not only gravity but also wind, the Earth's rotation, and other factors. To compile these tables before the invention of computers required the efforts of a huge number of mathematically inclined people, and was a very slow process; the need to make ballistic table computations quickly was one of the primary motivations for the development of modern computers.

Newton said that the force of gravitation acts between any two bodies possessing *mass*—which is related to the amount of material a body contains. The reason an arrow, a cannonball, or a dropped key falls to the ground is that there is a strong force of attraction between it and the planet. Since the planet is much bigger than these objects, they are the ones that do almost all the moving. Although the planet is also attracted to them, its movement under such circumstances is insignificant.

Newton discovered that the force due to gravitation between the two masses $m_1$ and $m_2$, whose centers are separated by a distance of *r*, is given by the equation

$$F = (Gm_1m_2) / r^2,$$

in which *G* is a number called the constant of gravitation. Force is usually described in units called newtons, as described in the sidebar on the next page. Gravitational attraction is proportional to the product of the masses: as either or both of the masses increase, so does the force. But the attraction is inversely proportional to the square of the distance: if the distance is made twice as great, the force is two squared or four times less.

The most important part about Newton's law of gravitation is that it is universal—this law applies to everything in the universe. This includes people, who attract one another in a gravitational sense as well as in an emotional sense. But gravitation is weak compared to other forces. For two average-sized adults standing 3.28 feet (1 m) apart, the gravitational attraction is 0.0000004 newtons—roughly equivalent to the weight of 0.00000009 pounds on the surface of the Earth, which is hardly strong enough to bring together two people who do not like each other's company. For objects that are electrically charged, electrical forces are vastly more powerful than gravity. So are magnetic forces—even a small magnet can hold up objects and defy the force of gravity.

One measure of the strength of Earth's gravity is how fast it can pull down a falling object. Although weak compared to other forces, gravity appears strong on Earth because the planet is so massive.

## The Metric System and SI Units

In order to describe the results of measurements, physicists need to use a system of units. Numbers alone are not good enough; to describe a distance as "3" is not useful—is the distance three inches or three miles or three meters? Many people in the United States use the English system of units: foot for distance, pound for weight, and second for time.

The system of units used by most of the world is the *metric system,* a logical system based on factors of 10. The unit of distance is the meter, which can be subdivided into tenths of a meter (decimeter), hundredths (centimeter), thousandths (millimeter), and even smaller amounts. Ten meters is a decameter, 100 is a hectometer, and 1,000 is a kilometer. In terms of the English system of units, one foot is approximately 0.3 meter, and one mile is approximately 1.6 kilometers. The metric unit of mass is the gram. Weight is the force of gravity acting on a mass, and on the surface of Earth a mass of one gram weighs 0.035 ounce. Since this is a small amount, the kilogram (1,000 grams) is often used; a kilogram weighs 2.2 pounds on Earth's surface.

The International System of Units was established in 1960. Called *SI units* (after the French term *Système International*), this system is like the metric system in its use of prefixes such as milli- (thousandth) and kilo- (thousand) to represent quantity.

One can calculate how fast an object should fall because Newton also discovered that the *acceleration* of a mass $m_1$ due to a force $F_1$ is $F_1/m_1$. (This is Newton's second law of motion, to be discussed in more detail in chapter 2.) If a person standing on the surface of the Earth drops a ball of mass $m_1$, one can determine how fast the ball will fall by writing the force of gravity as $F_1$ and plugging in the numbers $M_E$ for Earth's mass and $R_E$ for its radius (which is roughly the distance between the center of the ball and the center of Earth):

$$F_1 / m_1 = (Gm_1M_E) / m_1R_E^2 = GM_E / R_E^2.$$

The mass, $m_1$, of the ball cancels. (This cancellation assumes that the mass experiencing the force of gravitation is the same mass to which Newton's laws of motion apply. This is true as far as physicists have been able to determine.) The most surprising thing