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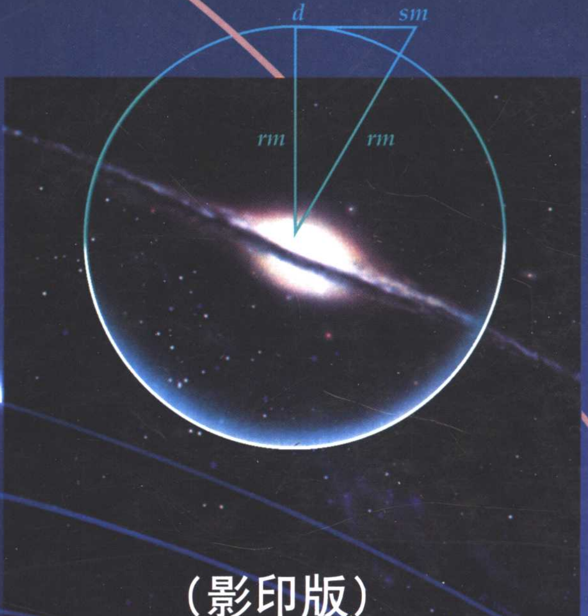
# THE MECHANICAL UNIVERSE

## INTRODUCTION TO MECHANICS AND HEAT

## 力学世界——力学和热学导论

RICHARD P. OLENICK, TOM M. APOSTOL
& DAVID L. GOODSTEIN

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# 英文影印版前言

为提高中国大学生英语交流能力，同时了解国外教学情况，推动英汉双语教学，美国 IET 基金会与中国教育电视台决定共同建设“IET 大学基础课程英语教学系列教材”。

在系列教材的开发工作中，IET 教育基金常务理事学校北京大学、清华大学、北京师范大学、北京航空航天大学、中国地质大学、北京科技大学、北方交通大学、对外经济贸易大学、石油大学、中国矿业大学给予了大力支持。

本物理教本是美国加州理工学院为非物理专业学生编写的。近年来，美国有 247 所大学选用本教材。教材配有音像课件、教师教学参考书、学生参考书等。

在本书的引进及审阅过程中，清华大学陈泽民教授、北京大学李椿教授、北京师范大学梁竹健教授、北京航空航天大学陈强教授、中央广播电视大学吴铭磊教授、北京师范大学漆安慎教授、北京大学王稼军教授做了大量工作；李椿教授、梁竹健教授等将本书译出中译本。在此一并致谢。

本书为美国原版影印教材，以英制为基本单位制。书后配有公/英制单位换算表，谨作说明。

IET 教育基金会
2001.12

# PREFACE

## I GENERAL INTRODUCTION

*The Mechanical Universe* is a project that encompasses fifty-two half-hour television programs, two textbooks in four volumes (including this one), teachers' manuals, specially edited videotapes for high school use, and much more. It seems safe to say that nothing quite like it has been attempted in physics (or any other subject) before. A few words about how all this came to be seem to be in order.

Caltech's dedication to the teaching of physics began fifty years ago with a popular introductory textbook written by Robert Millikan, Earnest Watson, and Duane Roller. Millikan, whose exploits are celebrated in Chapter 12 of this book, was Caltech's founder, president, first Nobel prizewinner, and all-around patron saint. Earnest Watson was dean of the faculty, and both he and Duane Roller were distinguished teachers.

Twenty years ago, the introductory physics courses at Caltech were taught by Richard Feynman, who is not only a scientist of historic proportions, but also a dramatic and highly entertaining lecturer. Feynman's words were lovingly recorded, transcribed, and published in a series of three volumes that have become genuine and indispensable classics of the science literature.

The teaching of physics at Caltech, like the teaching of science courses everywhere, is constantly undergoing transition. Caltech's latest effort to infuse new life in freshman physics was instituted by Professor David Goodstein and eventually led to the creation of *The Mechanical Universe.* Word reached the cloistered Pasadena campus that a fundamental tool of scientific research, the cathode-ray tube, had been adapted to new purposes, and in fact could be found in many private homes. Could it be that a large public might be introduced to the joys of physics by the flickering tube that sells us spray deodorants and light beer?

As the idea of using television to teach physics started to reach serious proportions, a gift was announced by Walter Annenberg, publisher and former U.S. Ambassador to Great Britain, to support the use of broadcast means for teaching at the college level. Ultimately, nearly $6 million of funds from the Annenberg School of Communications to the Corporation for Public Broadcasting through the Annenberg/CPB Project would be spent in support of *The Mechanical Universe.* That, in brief, is the story of how *The Mechanical Universe* came to be.

## II PREFACE FOR STUDENTS

Each chapter of this book corresponds to one program of *The Mechanical Universe* television series. The book can also be used in the more traditional way as a physics textbook, without the television series. We anticipate that you will read each chapter, view each program one or more times, and take advantage of further guidance, instruction, practice, and other help provided by institutions that offer this course for academic credit.

It seems only fair to warn you that *The Mechanical Universe* does not follow the traditional guidelines of the college physics curriculum in the United States. Quite aside from the use of television, we have taken a somewhat unconventional view of the relationship between physics, the historical, philosophical, and social context in which it arose, and the mathematics on which it is based. A special word is in order about the use and level of mathematics that will be required of you.

It is assumed that every student of *The Mechanical Universe* begins with a solid secondary-school background in algebra and trigonometry. Certain other aspects of mathematics that are essential to the understanding and appreciation of physics are presented as they arose historically, as an intrinsic part of the development of physics. These include the derivative (Chapters 2 and 3), vectors (Chapter 5), the reverse of differentiation (Chapter 6), integrals (Chapter 7), and, throughout the book as needed, the use of analytic geometry and differential equations. This list may seem intimidating, but we firmly believe that the material is presented in a way that puts it within your grasp and makes it worth the effort to assimilate.

The traditional American college curriculum includes a physics course based on algebra and trigonometry that attempts to teach physics without the help of calculus. With rare exceptions, the popularity of such a course rivals that of compulsory military service. Our view is that the fault lies neither with the teachers nor with the students, but rather with the misguided attempt to bowdlerize physics of its essential mathematical

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underpinnings. We sincerely hope that students of *The Mechanical Universe* will be inspired to take additional courses in calculus as part of their education in mathematics (just as we hope they will want to pursue further the issues raised here in history and philosophy), but the mathematics presented in this course is sufficient for its intended purpose of use in the study of physics.

Although most important ideas in this course are presented in the television series, many of them cannot be learned by simply watching television any more than they can be learned by simply listening to a classroom lecture. Mastering physics requires the active mental and physical effort of asking and answering questions, and especially of solving problems. The examples and questions interspersed through every chapter are intended to play an essential role in the process of learning.

The backbone of *The Mechanical Universe* is a series of events that began in 1543 with a book published by Copernicus and culminated a century and a half later with a view of the universe that, consciously or not, has formed the basis of virtually all human intellectual activity since then. It is our firm view that a thorough understanding of that revolution in human thought is essential to any serious education. Offering that knowledge in an innovative way is the purpose of *The Mechanical Universe*.

## III PREFACE FOR INSTRUCTORS AND ADMINISTRATORS

We expect that the ways in which *The Mechanical Universe* television series and textbooks are used will vary widely according to the circumstances and preferences of the institutions that offer it as a college course. The television programs can be viewed at home via broadcast or cable, presented in class, offered for viewing at the student's convenience at campus facilities, or even dispensed with altogether. However, we hope that no institution will imagine that the course can be presented without the services of live, flesh-and-blood college physics teachers. For most students, physics cannot be learned from a book alone, and it cannot be learned from a television screen either.

No laboratory component is offered as a part of *The Mechanical Universe* project. The reason is not that we judge a physics laboratory course to be unimportant or uninteresting, but rather that we judge its presentation by us to be impractical. We expect each institution offering the course to decide how it wishes to handle the laboratory component of learning physics.

This book is intended for use by students who would otherwise have taken the standard algebra- and trigonometry-based college physics course. Differential and integral calculus are treated just as vectors always have been in courses at this level: as subjects to be taught like any other portion of mechanics. For example, in Chapter 2 the mathematical concept of derivative is introduced in a natural way to explain the physical concepts of instantaneous velocity and acceleration. Chapter 3 describes further properties of derivatives, but is not to be considered a substitute for a course on differential calculus. Since this is a physics text rather than a mathematics text, our treatment of calculus is closely tied to intuitive and physical concepts. Thus, for example, in Chapter 7, the integral is defined in terms of area, and intuitive properties of area are used freely to derive corresponding properties of integrals. In a more rigorous treatment, as found in mathematics books, the integral is defined in terms of numbers (as a limit of a sum), and then the integral is used to define area. Care has been taken to present the mathematics in a way consistent with the views of mathematicians as well as physicists.

Some comments on the overall strategy of the presentation may be helpful. The necessary mathematics is mostly found in Chapters 3 (derivatives), 5 (vectors), 7 (integrals), and 9 (circular motion). These are interleaved with chapters that present physical ideas that, although profound and important (e.g., Chapter 4, inertia), require less homework practice than the mathematical ones. In addition, Chapters 2 and 6 purposely anticipate the ideas (respectively, derivatives and integrals) to be covered in the following chapters.

Chapter 6 seems to carry a particularly heavy burden. Not content with introducing Newton's laws, it also introduces some simple differential equations and their solutions. However, Chapter 4 has already laid the groundwork for understanding the trajectories worked out in Chapter 6, and the application of Newton's laws in other contexts is a persistent theme of following chapters, through Chapter 12 (the Millikan experiment).

There follow chapters on energy (13 and 14), heat, matter, and entropy (15–18), the conservation of momentum (19), harmonic motion (20–22), and angular momentum (23 and 24). Repetition and return to earlier ideas are not to be feared: Chapter 9 (circular motion) is designed partly as preparation for 23 and 24 (angular momentum), and Chapter 22 (waves) anticipates a series of chapters on aspects of waves to be found in the sequel to this volume, *Beyond the Mechanical Universe.*

As we stated above, each television program corresponds to one chapter of the book, and this is indicated in the table of contents. However, the programs for Chapters 15–18 (thermodynamics) will normally not be shown in a television broadcast of the first semester of *The Mechanical Universe,* although the videos will be made available to schools. Instead, in a broadcast "Energy and Stability" (Chapter 14/Program 14) will be followed immediately by "The Conservation of Momentum" (Chapter 19/Program 15). The textual material for these topics exluded from the programming sequence is included in the book because some instructors may wish to present a course covering both mechanics and heat.

The intellectual climax of this first volume is to be found in Chapters 25, 26, and 27, in which Newton's laws are used to solve the Kepler problem. In reality, Kepler's first law is derived in Chapter 23, and his third law must await Chapter 29. The deduction and analysis of elliptical orbits are the real payoff. This is where the student becomes master of *The Mechanical Universe,* so much so that Chapter 28 can be devoted to a discussion of how to navigate in space.

Throughout *The Mechanical Universe,* history is used as a means to humanize physics. It should go without saying that we don't expect students to memorize names and dates any more than we expect them to memorize detailed formulas and constants. *The Mechanical Universe* may or may not contribute to the vocational training of any given student. We hope it will contribute to their education.

## IV ACKNOWLEDGMENTS

*The Mechanical Universe* textbooks, like the television series itself, would not have been possible without the cheerful and dedicated work of a long list of people who aided in its realization.

Number one of the list is Professor Steven Frautschi, of Caltech, lead author of

the companion volume for science and engineering majors, who made countless valuable contributions to this book as well.

Special mention goes to *The Mechanical Universe* Local Advisory Committee, each member of which read and criticized in detail every chapter of the manuscripts, thus lending the benefit of their very considerable teaching experience: Keith Miller, Professor of Physics, Pasadena City College; Ronald F. Brown, Professor of Physics, California Polytechnic State University, San Luis Obispo; Eldred F. Tubbs, Member of the Technical Staff, Jet Propulsion Laboratory, Caltech; Elizabeth Hodes, Professor of Mathematics, Santa Barbara City College; and Eric J. Woodbury, Chief Scientist (retired), Hughes Aircraft Company.

In addition, parts of the manuscripts have been read and criticized by Margaret Osler (University of Calgary), Judith Goodstein (Caltech), and Robert Westman (UCLA), distinguished historians all; Dave Campbell (Saddleback Community College) and Jim Blinn (Jet Propulsion Laboratory), members of *The Mechanical Universe* team; Theodore Sarachman (Whittier College); and the entire 1983 and 1984 Caltech freshman classes.

In addition to all of these, homework problems were provided by Mark Muldoon and Brian Warr, and problems were checked for accuracy by Mark and Brian as well as by George Siopsis and Milan Mijic, all of Caltech.

Under the splendid direction of Project Secretary Renate Bigalke, the words and equations, mistakes and corrections of the authors were patiently and accurately rendered into the computer memory by Laurie Cornachio, Marcia Goodstein, and Sarb Nam Khalsa. All of the work was watched over anxiously by Hyman Field of the Annenberg/CPB Project (sponsors of *The Mechanical Universe*) and gently prodded along by David Tranah and Peter-John Leone of Cambridge University Press. We are especially pleased that Cambridge, which published Newton's *Principia*, has decided to follow it up with *The Mechanical Universe*. Sally Beaty, Executive Producer of *The Mechanical Universe* television series, was present and instrumental at every important juncture in the creation of these books. Geraldine Grant and Richard Harsh supervised an extensive formal evaluation of various components of *The Mechanical Universe* project, including drafts of the chapters from this volume; the results of that effort have had their due effect on the final work. Carol Harrison sniffed out many photos and their sources for us.

Finally, special thanks are due to Don Delson, Project Manager of *The Mechanical Universe*, who, through some miracle of organizational skill, cunning, and compulsive worrying, managed to keep the whole show going.

# CONTENTS

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# CHAPTER 1

# INTRODUCTION TO THE MECHANICAL UNIVERSE

In the center of all the celestial bodies rests the sun. For who could in this most beautiful temple place this lamp in another or better place than that from which it can illuminate everything at the same time? Indeed, it is not unsuitable that some have called it the light of the world; others, its mind, and still others, its ruler. Trismegistus calls it the visible God; Sophocles' Electra, the all-seeing. So indeed, as if sitting on a royal throne, the Sun rules the family of the stars which surround it.

Nicolaus Copernicus, *De Revolutionibus Orbium Coelestium* (1543)

## 1.1 THE COPERNICAN REVOLUTION

We find it difficult to imagine the frame of mind of people who once firmly believed the earth to be the immovable center of the universe, with all the heavenly bodies revolving harmoniously around it. It is ironic that this view, inherited from the Middle Ages and handed down by the Greeks, particularly Greek thought frozen in the writings of Plato and Aristotle, was one designed to illustrate our insignificance amid the grand scheme of the universe – even while we resided at its center.

Aristotle's world consisted of four fundamental elements – fire, air, water, and earth – and each element was inclined to seek its own natural place. Flame leapt through air, bubbles rose in water, rain fell from the heavens, and rocks fell to earth: the world was ordered. Each element strove to return to its sphere surrounding the center of the universe. But even as Aristotle ordered the world, he did not deem it perfect. It was subject to death and decay just as were its inhabitants. Perfection was reserved for the heavens alone, which were serene and immutable.

Above the sphere of fire were the crystalline spheres of the moon, planets, sun, and the stars beyond. Each heavenly body was fixed in its orbiting sphere, traveling across the sky in a circle – the perfect shape Plato deemed as the ideal path all cosmic bodies should follow. Thus conceived, the universe was so simple that it was fully and adequately represented in great clocks constructed and painted by craftsmen of the Middle Ages. And the motions of the heavenly bodies were like the inner workings of clocks – regular, predictable, and in the mind of man, free of earthly decay.

This scheme, this grand plan, was an effort to describe the environment as it presented itself to the human senses. It was an attempt to find one simple, all-encompassing explanation for natural phenomena. The modern era began when people began to ask questions that Aristotle's world view could not answer.

Our purpose is to understand what has come to be known as classical mechanics – the science that arose to answer those new questions. No discovery in human thought is more important. Through it the temple of Aristotelian thought collapsed and no less than a new view of our place in the universe gradually rose from its ashes to replace it. So before we start to study physics, let's introduce some of the principal heroes of the story that we're going to see unfold.

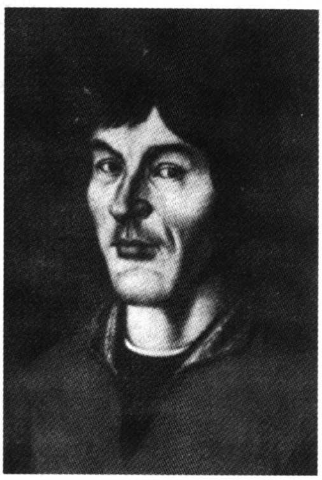

Figure 1.1 Nicolaus Copernicus (1473–1543). (Courtesy of the Polish Cultural Institute in London.)

Nicolaus Copernicus, a timid monk who lived from 1473 to 1543, began the revolution with his book *De Revolutionibus Orbium Coelestium*, or *On the Revolutions of the*

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