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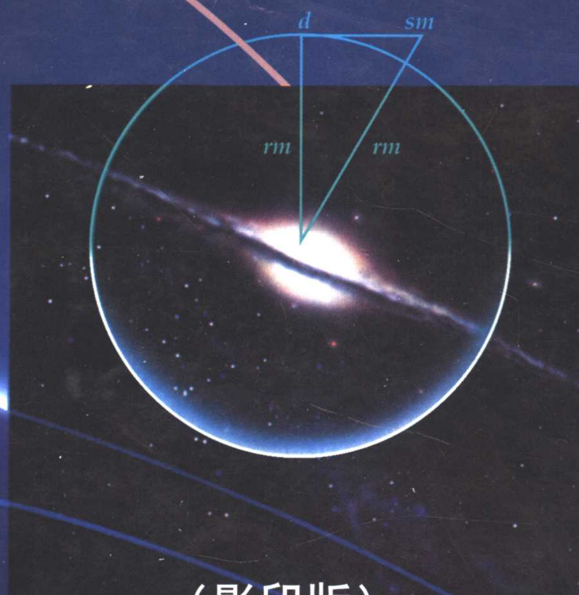
BEYOND THE MECHANICAL UNIVERSE

FROM ELECTRICITY TO MODERN PHYSICS

力学以外的世界——从电学到近代物理

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



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FROM ELECTRICITY TO MODERN PHYSICS

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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 (repeated from the first volume, *Introduction to Mechanics and Heat*)

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. Of the three, 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 Mr. Annenberg's funds, administered by the Corporation for Public Broadcasting, 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

Just as in the first volume, 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. As before, 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.

In the opening sequence of each television program, the viewer zooms into space, past asteroids, moons and planets, and beyond distant Pluto, pausing at the words *The Mechanical Universe*. For the second half of the series there also appear the words ... *and Beyond*, to indicate that we are now passing beyond mechanics, into other realms of physics.

And indeed we are. This second volume studies electricity and magnetism, their relation to each other and to light, and shows how the problem of light led to the special theory of relativity. Finally, we enter the world of modern physics, where particles may behave like waves and vice versa, and where some of the great verities of Newtonian physics appear less certain than they had.

In the course of all this, a few familiar mathematical tools from calculus are called into action and some new ones are introduced. For example, integrals along paths and integrals over surfaces are particularly useful for describing electric and magnetic fields. However, while it is important to understand the ideas expressed by these operations, they are seldom used for computation, and then only in the simplest cases.

That is not to say that our journey through this volume will be effortless. Our job is to go from the conclusion of one revolution in science – the discovery of Newtonian mechanics – to the beginning of another – the discovery of quantum mechanics. The end of the journey takes us close to the limits of human thought. If the journey is sometimes arduous, there is nevertheless quite a lot of remarkable scenery along the way, and considerable intellectual reward for reaching the goal.

Most of the important ideas in this course are presented in the television series, but 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 working out problems. The examples and questions interspersed through every chapter are intended to play an essential role in the process of learning.

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 because 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 have served their apprenticeship with the first volume of *The Mechanical Universe*, *Introduction to Mechanics and Heat*. We assume a level of mathematical sophistication attained by readers of that volume – basic skills with derivatives, integrals, and vectors, and some familiarity with differential equations. We do not assume that the student has read the unit on Heat (Chapters 15–18), which many schools prefer to offer after relativity (Chapters 45–48). The present volume allows this flexibility in the order of topics.

Throughout *The Mechanical Universe*, *and Beyond*, 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 the education of all of them.

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.

First of all, Professor Steven Frautschi, of Caltech, lead author of the companion volume for science and engineering majors, made contributions to this volume as well.

The authors benefited from comments made by *The Mechanical Universe* Local Advisory Committee: 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, Mario Iona (University of Denver) carefully reviewed the entire text and Judith Goodstein (Caltech) checked the manuscript for historical accuracy. The authors also received input from Dave Campbell (Saddleback Community College) and Jim Blinn (Jet Propulsion Laboratory), members of *The Mechanical Universe* team, and from Robert J. Sirko (Manager of Technology Planning for the Space Station Program at McDonnell Douglas Astronautics Company).

Special thanks go to Sharon Cox (University of California, Irvine) whose careful reading uncovered a number of technical errors in the original draft. She also made valuable suggestions for improving the exposition, and skillfully worked out the solutions to most of the problems.

Project Secretaries Renate Bigalke, Gwen Anastasi, Sarb Nam Khalsa, and Debbie Bradbury provided expert assistance in all phases of manuscript preparation, from word processing to obtaining permissions for reproducing copyrighted material. Carol Harrison sniffed out many photos and their sources for us, and Greg Borse located many historical references. Science Typographers, Inc., did a splendid job of copy editing, typesetting, and preparation of illustrations.

All of the work was watched over by Hyman Field of the Annenberg/CPB Project (sponsors of *The Mechanical Universe*) with the help of Peter Combes, and was 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; the results of that effort have had their due effect on the final work.

Finally, special thanks are due 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

CHAPTER 31

BEYOND THE MECHANICAL UNIVERSE

I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.

Isaac Newton, from Brewster, *Memoirs of Newton* (1855)

31.1 SCIENCE AFTER NEWTON

The first volume of this series was largely devoted to the story of the first scientific revolution, and its consequence, the rise of the mechanical universe. It began with a Polish monk who wondered whether the universe might not look simpler from a different point of view, and it culminated with Isaac Newton, who gave us a wealth of scientific discoveries and a coherent view of the universe and how it ought to be described.

Not that Newton had discovered everything worth knowing – far from it. When he described himself as a child picking an occasional pretty pebble from the beach while a vast ocean of knowledge lay undiscovered before him, he meant precisely that science was in its infancy. But Newton had given us a way of organizing the unknown into questions that had answers. The world consists of matter and of forces, which together produce motion. The motion could be analyzed using his mechanics and his calculus. The questions that remained were, what are the forces of nature, and what is matter made of? One could add more detailed questions, such as, what is light, and what is life?

And so the world set out to provide Newtonian answers to all scientific questions. To be sure, not all the world undertook that task. Then, as always, most people were preoccupied with the more mundane aspects of simple survival, while the more powerful among them concerned themselves with the larger issues, such as making money, making war, spreading religion, and running slaves. But, throughout the 200 years that followed Newton's time, there were always a few who found the opportunity to pursue the goal of reducing natural phenomena to orderly, rational, Newtonian explanations.

They made a great deal of progress. Among the first issues taken up were the phenomena of electricity and magnetism. Both had been known to exist since antiquity, and had been observed and even made use of by various scholars. Their effects were examined with increasing precision and the results were quantified. Finally, the theory was described mathematically according to Newtonian precepts. As we have already seen in Chapter 11, this process reached its climax around the time of the American Civil War, when James Clerk Maxwell realized that the speed of light could be found by combining the static forces between electric charges with that between magnetic poles. Starting from this synthesis, he worked out an elegant theory that combined electricity, magnetism, and light into a single phenomenon. Maxwell's theory is the ultimate objective of the next 12 chapters of this book.

In the meantime, other Newtonian scientists had turned their attention to the properties of matter. Among these was a group of chemists who revived the ancient idea of the atomic theory of matter. Throughout the nineteenth century, those intrepid investigators broadened their knowledge of chemical elements and how they combined, and sought to learn how their properties could be explained from the nature of their constituent atoms. Another group of scientists perceived profound implications in the rules governing the flow of heat, and brought forth an astonishingly successful new axiomatic science called thermodynamics.

And then, at the dawn of the twentieth century, a strange thing happened. Suddenly, the whole Newtonian system didn't seem to work so well anymore. Of course, it was just as good as ever at explaining the orbit of the moon or the trajectory of a cannonball, but new phenomena appeared that were not so much beyond Newtonian science as inconsistent with it, or even contradictory to it.

For example, the law of inertia, which is at the very basis of Newtonian mechanics, makes perfect sense so long as any one speed is as good as any other, there being no state of absolute rest from which to measure absolute speed. But Maxwell had shown that there was an absolute speed – the speed of light. Was the law of inertia consistent with a universe in which light could propagate through the