BEYOND THE MECHANICAL UNIVERSE
BEYOND THE MECHANICAL UNIVERSE
FROM ELECTRICITY TO MODERN PHYSICS

RICHARD P. OLENICK
ASSISTANT PROFESSOR OF PHYSICS, UNIVERSITY OF DALLAS
VISITING ASSOCIATE, CALIFORNIA INSTITUTE OF TECHNOLOGY

TOM M. APOSTOL
PROFESSOR OF MATHEMATICS, CALIFORNIA INSTITUTE OF TECHNOLOGY

DAVID L. GOODSTEIN
PROFESSOR OF PHYSICS AND APPLIED PHYSICS, CALIFORNIA INSTITUTE OF TECHNOLOGY
AND PROJECT DIRECTOR, THE MECHANICAL UNIVERSE
CONTENTS

PREFACE xi

CHAPTER 31 BEYOND THE MECHANICAL UNIVERSE (Program 27)  1
   31.1 Science After Newton  1
   31.2 Orders of Magnitude  4
   31.3 A Final Word  11
Chapter 32 STATIC ELECTRICITY (Program 28) 13

32.1 The Beginnings of Electrical Science 13
32.2 The Electroscope 16
32.3 Charge Separation and Induction 17
32.4 Coulomb’s Law 20
32.5 Electrostatic Machines 26
32.6 A Final Word 29

Chapter 33 THE ELECTRIC FIELD (Program 29) 31

33.1 Electric Fields of Isolated Point Charges 31
33.2 Electric Fields of Continuous Charge Distributions 37
33.3 Electric Flux 44
33.4 Gauss’s Law 47
33.5 Applications of Gauss’s Law 51
33.6 Electric Fields and Conductors 57
33.7 A Final Word 61

Chapter 34 POTENTIAL AND CAPACITANCE (Program 30) 63

34.1 A Great American Scientist 63
34.2 Electric Potential 64
34.3 Electric Energy of Systems of Charges 74
34.4 Capacitors 77
34.5 Combinations of Capacitors 82
34.6 Energy Storage in a Capacitor 86
34.7 A Final Word 89

Chapter 35 VOLTAGE, ENERGY AND FORCE (Program 31) 91

35.1 Electric Fields and Potentials 92
35.2 Equipotential Surfaces 97
35.3 Voltages in the World 101
35.4 Charge Distribution on Conductors 107
35.5 A Final Word 110

Chapter 36 THE ELECTRIC BATTERY (Program 32) 113

36.1 Frog Legs and Electricity 113
36.2 The Workings of Metals 115
36.3 Battery Basics 123
36.4 Real Batteries 126
36.5 A Final Word 127
## CONTENTS

### Chapter 37 ELECTRIC CIRCUITS (Program 33) 129

37.1 The Invention of the Telegraph 129  
37.2 Electrical Conduction in Wires 131  
37.3 Ohm’s Law 134  
37.4 Resistors Connected in Series and in Parallel 139  
37.5 Kirchhoff’s Laws 144  
37.6 RC Circuits with Variable Currents 151  
37.7 A Final Word 157

### Chapter 38 MAGNETISM (Program 34) 159

38.1 Lodestones and Magnetic Needles 159  
38.2 Forces and Magnetic Fields 162  
38.3 Magnets and Torques 169  
38.4 Gauss's Law for Magnetism 171  
38.5 Magnetic Force on Moving Charges 174  
38.6 Magnetic Force on Currents 183  
38.7 A Final Word 188

### Chapter 39 THE MAGNETIC FIELD (Program 35) 191

39.1 The Connection between Electricity and Magnetism 191  
39.2 The Law of Biot and Savart 193  
39.3 Force between Current-Carrying Wires 204  
39.4 Ampère’s Law 207  
39.5 A Final Word 215

### Chapter 40 VECTOR FIELDS AND HYDRODYNAMICS (Program 36) 217

40.1 Action-at-a-Distance Revisited 217  
40.2 Properties of Vector Fields 218  
40.3 Flux of a Vector Field 219  
40.4 Circulation of a Vector Field 222  
40.5 Hydrodynamic Analogies for Energy and Forces 232  
40.6 A Final Word 233

### Chapter 41 ELECTROMAGNETIC INDUCTION (Program 37) 235

41.1 The Incomparable Experimentalist 235  
41.2 Observations of Electromagnetic Induction 237  
41.3 Faraday’s Law 245  
41.4 Lenz’s Law 251  
41.5 Self-Inductance 256  
41.6 Mutual Inductance 259  
41.7 LR Circuits 263
41.8 Energy and Magnetic Fields 267
41.9 A Final Word 269

Chapter 42 ALTERNATING CURRENTS (Program 38) 273
42.1 Two Great Inventors 273
42.2 Alternating Currents in Simple Circuits 276
42.3 LC Circuits 280
42.4 LCR Circuits 282
42.5 Power in ac Circuits 288
42.6 Transformers 291
42.7 A Final Word 294

Chapter 43 MAXWELL’S EQUATIONS (Program 39) 295
43.1 A Victorian Genius 295
43.2 The Link between Electricity and Magnetism 296
43.3 Maxwell’s Equations in Free Space 301
43.4 Plane Waves Moving with Constant Speed 302
43.5 The Wave Equation 303
43.6 Electromagnetic Waves 307
43.7 Disturbances Caused by Accelerated Charges 312
43.8 A Final Word 314

Chapter 44 OPTICS (Program 40) 317
44.1 The Electromagnetic Spectrum 317
44.2 The Nature of Light 323
44.3 Reflection and Refraction 325
44.4 Interference of Light Waves 332
44.5 A Final Word 341

Chapter 45 THE MICHELSON – MORLEY EXPERIMENT (Program 41) 343
45.1 The Roots of Relativity 343
45.2 The Galilean Transformation 345
45.3 Space–Time Diagrams for Galilean Transformations 351
45.4 Relativity and the Nature of Light 354
45.5 The Michelson–Morley Experiment 356
45.6 A Final Word 363

Chapter 46 THE LORENTZ TRANSFORMATION (Program 42) 367
46.1 Interpreting the Michelson–Morley Experiment 367
46.2 The Postulates of the Special Theory of Relativity 369
46.3 The Lorentz Transformation 372
CONTENTS

46.4 Length Contraction 378
46.5 Space–Time Diagrams 382
46.6 A Final Word 386

Chapter 47 VELOCITY AND TIME (Program 43) 389

47.1 Proper Length and Proper Time 389
47.2 Combinations of Velocities in Special Relativity 392
47.3 The Fizeau Experiment 397
47.4 The Muon Experiment 399
47.5 The Twin Paradox 402
47.6 A Final Word 405

Chapter 48 MASS, MOMENTUM, ENERGY (Program 44) 407

48.1 Inertia and Relativity 407
48.2 Momentum and Mass 408
48.3 Relativistic Kinetic Energy 417
48.4 Applications of Conservation of Relativistic Energy and Momentum 424
48.5 A Final Word 427

Chapter 49 ATOMS (Program 49) 431

49.1 Early History of Atomic Theory 431
49.2 Experimental Evidence Supporting Atomic Theory 432
49.3 The Atomic Structure of Matter 435
49.4 Rutherford’s Model of the Atom 439
49.5 Spectra of Electromagnetic Radiation 444
49.6 The Bohr Model of the Atom 448
49.7 A Final Word 453

Chapter 50 PARTICLES AND WAVES (Program 50) 455

50.1 Black Body Radiation 455
50.2 The Photoelectric Effect 459
50.3 The Dual Nature of Light 463
50.4 The De Broglie Model of the Hydrogen Atom 466
50.5 The Birth of Quantum Mechanics 470
50.6 The Quantum Mechanical Model of the Atom 478
50.7 The Heisenberg Uncertainty Principle 483
50.8 A Final Word 488

Chapter 51 ATOMS TO QUARKS (Program 51) 491

51.1 The Nature of Matter 491
51.2 Quantum States of the Hydrogen Atom 492
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.
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.