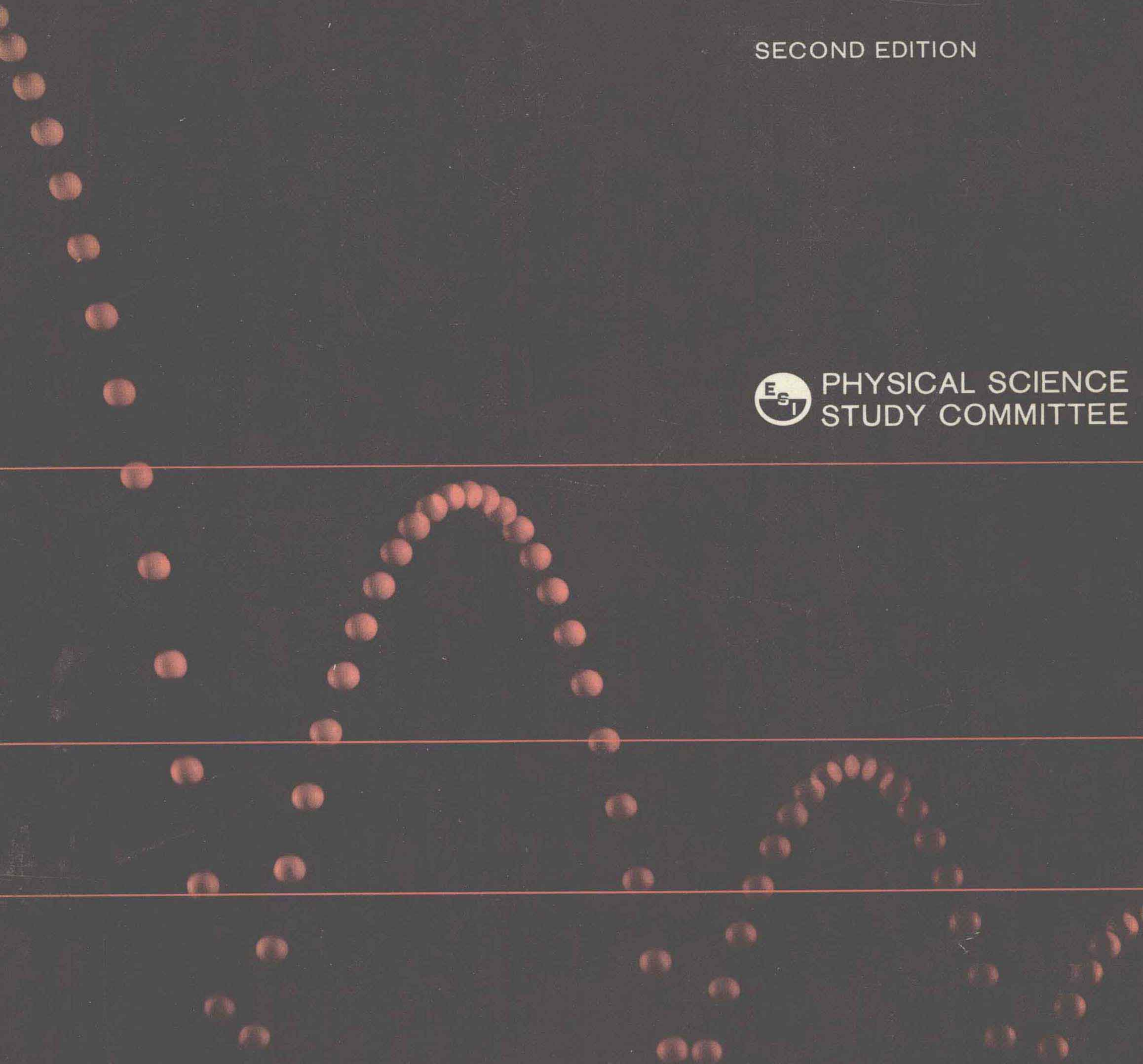
physics

SECOND EDITION

PHYSICAL SCIENCE
STUDY COMMITTEE



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SECOND EDITION

D. C. Heath and Company

BOSTON

LIBRARY OF CONGRESS CATALOG CARD NUMBER 65-24096

Published by D. C. Heath and Company BOSTON ENGLEWOOD CHICAGO SAN FRANCISCO ATLANTA DALLAS LONDON TORONTO

Under arrangements with Educational Services Incorporated

Printed January 1966

Preface to the second edition

REVISIONS for the second edition of PSSC Physics have been carried out in the light of the experience accumulated over the five years since the publication of the first edition. During this time, the course has been taught by some 6000 teachers to 640,000 students. We are deeply indebted to many of these teachers, and to some of their students, who have kept us informed of their successes and their tribulations through the "feedback" channels maintained for that purpose. We are also grateful to numerous colleagues from colleges and universities all over the world who have given us the benefit of their detailed criticisms of various chapters and sections. Throughout this period, the PSSC Planning Committee has been active in critically reexamining the existing materials and in both suggesting and producing new materials for trial in schools. This tested material has been particularly valuable in producing the second edition.

The major rewriting was done in Chapter 31, *Electromagnetic Induction and Electromagnetic Waves*, in order to place the entire discussion on a more experimental foundation and to improve upon the validity of one or two theoretical arguments. These changes in Chapter 31 necessitated some rearrangement and addition to Chapter 30, *The Magnetic Field.*

A change of emphasis in Chapters 5 and 6, in the treatment of kinematics and vectors, was also felt to be desirable as a means to increase the clarity of presentation of this material. Greater care has been exercised in both the definition and the use of terms in these chapters in the hope that students will see more clearly the difference between scalar and vector quantities.

There has been some shortening of the text where this could be done without damage to the logic and continuity of the course. Chapters 7 and 8 were reorganized into a more simple format and the sections on molecules and chemical structures have been rewritten as an essay at the end of Chapter 8, to be read for pleasure but not studied with the same intensity as the other material. The sections on lenses in the previous Chapter 14 have been combined here with Chapter 13, *Refraction,* and the sections on optical instruments have been deleted. Chapter 29 of the first edition has been divided into two parts, Chapter 28, *Energy and Motion of Charges in Electric Fields,* and Chapter 29, *Electric Circuits,* in order to emphasize the considerable amount of material included here on circuits. Several other sections of the book have been reorganized or reworded in an effort to clear up the points on which criticism has centered.

End-of-chapter problems have been extensively revised and improved, both in overall quality and in uniformity of coverage. An entirely new type of problem has been devised in direct response to teacher "feedback." These problems, marked with an asterisk and a section reference number, are short questions dealing only with material found in the indicated section, and designed to show a student whether or not he understands the basic points of that section. Answers for these problems are given in the back of the book. These are in no sense simply "plug-in" problems, but require careful thought about a very limited part of the subject. Teachers who have pilot-tested these problems during the past year have been unanimously enthusiastic about their usefulness and their quality.

Considerable effort in this revision has gone into improving the quality and the clarity of both photographs and line drawings. We have made every effort to continue the policy of large figures, either exhibiting phenomena or explaining situations of importance to the development of the logic of the text.

In the best tradition of the course, the relation between the text and the laboratory has been strengthened by the addition of several new and frequently crucial experiments to the laboratory. Most of the new experiments occur in Part IV of the course in order to increase the students' experience and experimental evidence in electricity, magnetism, and atomic structure. To make room for these additions, several experiments from the first edition have been either deleted, or it has been suggested that they be used as classroom demonstrations.

It has been our earnest effort to retain both the spirit and the content of the original course, making changes primarily for the purpose of strengthening or clarifying the arguments. It is only through actual use in the schools that we shall be able to estimate the results of this effort.

Preface to the first edition

THE PHYSICAL Science Study Committee is a group of university and secondary school physics teachers working to develop an improved beginning physics course. The project started in 1956 with a grant from the National Science Foundation, which has given the main financial support. The Ford Foundation and the Alfred P. Sloan Foundation have also contributed to the support of the program.

This textbook is the heart of the PSSC course, in which physics is presented not as a mere body of facts but basically as a continuing process by which men seek to understand the nature of the physical world. Besides the textbook there are the following closely correlated parts: a laboratory guide and a set of new and inexpensive apparatus; a large number of films; standardized tests; a growing series of paperback books by leaders in related fields; and a comprehensive teacher's resource book directly related to the course.

The PSSC physics course is the work of several hundred people, mainly school and college physics teachers, over a period of four years. A brief account of this collaboration is given in the next section, titled *The Development of This Book*. Here it is appropriate, however, to recognize two of these collaborators. Professor Jerrold R. Zacharias, of the Department of Physics of the Massachusetts Institute of Technology, called together a committee of leaders in physics and in education from which this project sprang. He has been active in all phases of the project. Professor Francis L. Friedman, also of the Department of Physics at MIT and a member of the Committee from the beginning, has played the major role in developing the textbook and has contributed significantly to all parts of the program.

In many ways this new course differs markedly from the beginning physics course usually taught in the United States. To be sure that the new approach was sound and teachable, the help of teachers and students was sought. In 1957–58, eight schools and 300 students tried out the early materials. Their comments and suggestions helped to improve and extend the content and approach. Then in 1958–59 nearly 300 schools and 12,500 students used the course, and in 1959–60 almost 600 schools and 25,000 students participated in the third test year. The course was thoroughly revised in the light of this experience.

The reactions of teachers and students show that a large percentage of students are intrigued by this course and do well with it. Their concepts grow through exploration in the laboratory, analysis in the text, and study of the films. The course appeals to students who are inclined toward the humanities as well as to those who are already interested in science.

The PSSC course consists of four closely interconnected parts. Part I is a general introduction to the fundamental physical notions of time, space, and matter: how we grasp and how we measure them. As the student learns of the almost boundless range of dimensions from the immensely large to the infinitesimally small, from microseconds to billions of years, he finds out how these magnitudes can be measured. He learns that instruments serve as an extension of his senses. Laboratory experience shows how we first measure by direct counting and then extend our range of measurements by calibrating and using simple instruments such as stroboscopes or range finders.

From these experiments measuring time and space, the student moves to an understanding of velocity and acceleration, of vectors and of relative motion. He then goes on to study matter, which we see moving through space in the course of time. In this first examination of matter, we develop the concepts of mass and of its conservation. We then use the evidence of physicists and chemists to find that matter is made of relatively few kinds of atoms. Direct experience is provided in the laboratory. There, for instance, the students compute the size of a molecule from measurements of thin films of oil. Moving pictures extend this direct laboratory experience by showing experiments which are beyond the reach of students.

Throughout, the student is led to realize that physics is a single subject of study. In particular, time, space, and matter cannot be separated. Furthermore, he sees that physics is a developing subject, and that this development is the imaginative work of men and women like him.

The topics in the PSSC course are selected and ordered to progress from the simple and familiar to the more subtle ideas of modern atomic physics. In Part I we have looked at a broad picture of the universe. Now as we examine certain fields of physics in more detail, we start in Part II with light. We live by light, and the student moves easily into a study of sharp and diffuse shadows, reflection in mirrors, and the refraction of light at optical boundaries. The natural development of the subject leads us to develop a particle theory (or model) of light. Its discussion illustrates repeatedly the manner in which virtually all scientific knowledge develops. Again films—for instance, the film on the pressure of light—help the student to go beyond the laboratory.

Under continued scrutiny the particle model proves inadequate, and the student finds that we need another model—a wave model. The laboratory again provides an unexcelled source of experience, and here the student becomes familiar with the properties of waves. He observes the behavior of waves on ropes and on the surface of water. He begins to recognize the group of characteristics that constitute wave behavior. Knowledge of interference and diffraction comes directly from a study of waves in a ripple tank. For the first time, perhaps, the smears of light around street lamps, the colors of oil slicks, and the formation of images by lenses appear as aspects of the wave nature of light.

During the first half of the course, the principal emphasis is on the kinematics of our world: where things are, how big they are, and how they move, not why. In Part III we turn to a closer look at motion, this time from a dynamical point of view. With simple laboratory apparatus the students discover Newton's law of motion. They learn to predict motions when forces are known and to determine forces when motions are known. Thus armed they follow the extraordinary story of the discovery of universal gravitation, Newton's educated guess with which he jumped from the known laws of motion to the law of gravitational attraction.

The laws of conservation of momentum and of energy are introduced through a combination of theory and laboratory exploration. These laws form a substantial portion of Part III, and we stress their use in situations where detailed observation of the motion is not possible, as in Chadwick's discovery of the neutron and in the kinetic theory of gases.

Part IV introduces the student to electricity and through it to the physics of the atom. Here the student uses the knowledge of dynamics gained in Part III. We begin with qualitative observations, then proceed to a quantitative study of the forces between charges. We learn how to measure very small electric forces and discover that electric charge comes in natural units. We then study the motion of charged particles in electric fields and learn how to determine the masses of electrons and protons.

Next comes a discussion of magnetic fields produced by magnets and currents, and a discussion of the forces they exert on moving charges. As a final part of electricity we discuss the induction laws and give the student a qualitative feeling for the electromagnetic nature of light. Many of the fundamental ideas are explored in the laboratory—Coulomb's Law, the magnetic field around a current, the force exerted by a magnetic field on a current-carrying wire are examples.

Now we use the knowledge gained on a large scale to probe the structure of atoms. Following the work of Rutherford, we establish the nuclear model of the atom. But some questions are unanswered. Why, for example, is such an atom stable? Why doesn't it collapse by emitting light? In searching for answers, we discover that light is both grainy and wavy.

Furthermore, we find that although matter behaves like particles, in some respects it also behaves like waves. By combining both properties, we can understand the stability of the hydrogen atom and the structure of its energy levels. In this part of the course, because direct experimentation becomes harder and more expensive, films bring to the student such experiments as the Millikan experiment and the interference of photons. At the end of the course we have arrived at the modern model of atoms.

The PSSC course as now presented has proved to be thoroughly teachable. It is useful in a wide variety of schools. However, those who have collaborated in building this course wish to improve it further. As the Physical Science Study Committee continues this development, your comments will always be welcome.

James R. Killian, Jr.
Chairman, Board of Trustees
Educational Services Incorporated
September 1960

The development of this book

THIS BOOK and the coordinated development of laboratory materials, teachers' resources, and films are the cooperative work of many people. Any brief summary of its development is bound to be unsatisfactory. Even the basic outline and aims were formulated by a large number of people at several centers, and teachers all over the country shared the desire to make a fundamental change in the presentation of physics for beginning students.

The present book is the result of innumerable individual contributions, of extensive trials in many schools, and of a process of revision over three years. To assign detailed credit for the creation and formulation among the hundreds of contributions is impossible. Nevertheless, as the person who took the responsibility for the selection that now appears, I should like to sketch some of the stages. Above all, both on behalf of the PSSC and also personally, I wish to thank my many co-workers for their part in the difficult but pleasurable experience of working together to bring forth a new physics course.

During the fall of 1956 and the winter of 1957, under the leadership of the PSSC Steering Committee, research physicists and physics teachers—often they are the same people—outlined, drafted, and discussed many of the ideas that now appear in this book. Then at Massachusetts Institute of Technology during the summer of 1957 some 60 physicists, teachers, apparatus designers, writers, artists, and other specialists pooled their knowledge and experience to produce a pilot model of the PSSC physics course.

In common with every section of the course, Part I of this book benefited from the work and the discussions of the group as a whole. In particular, it arose largely from the initial discussions of a group at Cornell University, especially Professors K. I. Greisen, Philip Morrison, and Hans A. Bethe. The job of making a complete first draft was carried out during the summer by Professor Morrison, with the help of George L. Carr now of Milford Mill High School, Baltimore, Maryland, and John Marean of Reno High School, Reno, Nevada. With slight rewriting, this draft, edited by Judson B. Cross of Phillips Exeter Academy, Curtis Hinckley of Woodstock Country School and me, formed the basis of the first school tryouts.

From the beginning, work in school has been a major part of the program. The teachers have been among the authors. To keep in touch, there has been an extensive program of school visiting and meetings between teachers and editors. Every part of the book has been improved by this process of testing and revision. For example, several sections of Part I have been revised three times. On the whole, the revisions, again tested in school, have proved their worth, and at the same time an astonishing amount of the original conception remains basically unchanged. We are particularly grateful for the efforts of the teachers who tried the earliest versions and who spent large amounts of time analyzing their experience. By now we have benefited by the experience of over 600 teachers and innumerable students. Their impressions and suggestions were collected and digested by a feedback team. Professor Gilbert Finlay of the College of Education at the University of Illinois has been in charge of this part of the job, and has contributed to the whole project in many ways.

In revising Part I at various times the special work of the group at the University of Illinois, that of Walter Michels at Bryn Mawr, and Sherman Frankel at the University of Pennsylvania was combined with more contributions from Professor Morrison and with the work of the staff at the central office of PSSC. For the present edition, further revision based on more experience in school has been provided by Malcolm K. Smith, Thomas Dillon of Concord High School, Concord, Massachusetts, Professors Eric M. Rogers of Princeton University, Nathaniel H. Frank of MIT, and me.

Most of the discussions and the preliminary development of apparatus that led to Part II of this book took place at the Massachusetts Institute of Technology. There, with the aid of Professor Walter Michels and Elbert P. Little, later assistant to the president of Educational Services Incorporated, I prepared an extensive outline. Following this, the first half of the volume was drafted by Professor Michels and Charles Smith of the Radnor High School, Radnor, Pennsylvania; the second half by Professors Uri Haber-Schaim and Arthur Kerman of MIT with Richard Jones of Indian Springs School, Helena, Alabama, and Darrel Tomer of Hanford High School, Hanford, California. Judson B. Cross and I edited the preliminary edition. Since that time it has had a history of tryout and revision similar to that of all the other parts. In particular, revisions for the present edition were carried out by Professor Haber-Schaim, Malcolm K. Smith, Professor Kerman, and me.

Most of the preliminary discussions leading to Part III took place in a group working at the University of Illinois. Then at MIT in the summer of 1957, Professors E. L. Goldwasser, Peter Axel, David Lazarus, Leon Cooper, and Allen C. Odian of the Illinois group worked with Thomas J. Dillon, Richard G. Marden of Worcester Classical High School, and John H. Walters of Browne and Nichols School to produce the first complete draft. Later Part III was considerably redrafted at PSSC to take advantage of the first draft, of suggestions from many physicists and teachers, and of new laboratory developments carried out by the PSSC staff in Cambridge. In this process Professor Bruno B. Rossi, Professor Frank, and I (all of MIT), were joined by Professor Eric M. Rogers and Malcolm K. Smith. So many members of the PSSC staff, both at MIT and the University of Illinois, contributed that it is even less possible here than elsewhere to give a fair impression of their joint efforts.

The first half of Part IV, dealing with electricity and magnetism, was originally drafted by Professor Rossi with the help of Alexander Joseph of the Bronx Community College, Bronx, New York, Thaddeus P. Sadowski of North Quincy High School, Quincy, Massachusetts, and Edwin Smith, Withrow High School, Cincinnati, Ohio. Also, starting in the summer of 1957, Professors Herman Feshbach and Roy Weinstein of MIT worked on the job of bringing as much modern atomic physics as possible from the last years of college physics to within reach of beginning students. Following after this and other preliminary work, Professor Morrison, Professor Rossi, and I laid out most of the present structure of Part IV, and drafts of the text were produced mainly by Rossi and Morrison. Malcolm K. Smith, Professor Rogers, Professor Frank, and I have been responsible for bringing the comments of teachers to bear on these drafts and for such rewriting and editing as has resulted in the present edition. Here we must particularly thank Professor James H. Smith of the University of Illinois, who tried some of these materials in preliminary form and pointed out the advantage of one radical change in order. We are also especially indebted to Richard Brinckerhoff of Phillips Exeter Academy for detailed commentary not only in this part but throughout the text, and to David A. Page of the University of Illinois, whose careful classroom observations were of great value especially in improving the earlier parts. To their names a great number should be added if space permitted.

In this kind of sketch, it is clear that many people are left out, especially if there is no one thing to which their names are obviously attached. Such omissions are painful: often enough, wise advice has been as valuable as an identifiable draft of text. Along these lines, then, I would like to mention the overall contributions of many others. Professor I. Bernard Cohen of Harvard University has read successive drafts and supplied historical materials. Stephen White, whose main concern has been with the PSSC films, has helped with other jobs from time to time since the beginning of the Committee's work. Paul Brandwein of Harcourt, Brace & Company and the Conservation Foundation has supplied detailed criticism, encouragement, and aid at many times. For instance, along with George H. Waltz, Jr., he helped to set up the effective system which turned authors' scrawls into respectable preliminary editions. In this process we benefited from the editorial experience of Judy Meyer and Lee Wertheim. Judson B. Cross and Malcolm Smith acted as executive editors of the preliminary volumes. For three years their work and mine has been lightened and made effective by the efforts of Benjamin T. Richards, who supervised the production of the texts for schools. Over the last year we have been joined by Richard T. Wareham, of D. C. Heath and Company, who smoothed the transition into this edition.

In this book the illustrations are essential. They were created by cooperative work between the illustrators, photographers, and physicists. Peter Robinson and Percy Lund have worked hard to make their illustrations meet our needs. James Strickland and Berenice Abbott have worked together to produce many of the excellent photographs; others were taken by Charles Smith, Ben Diver, Phokion Karas, Robin Hartshorne, Paul Larkin, and (in Part III) by Professor Chalmers Sherwin and Louis Koester of the University of Illinois. Special film clips were supplied by the Educational Services Incorporated film studio, where work on the related films has gone on in close collaboration.

The preliminary editions and the classroom work of teachers were essential to the process of developing this course. In utilizing them to bring about further improvements, the work of Gilbert Finlay and his co-workers, who stayed in close touch with teachers, was supplemented by information gathered directly from testing of students. Here Walter Michels made another of his many contributions. With Frederick L. Ferris, Jr., of Educational Testing Services and a group of physicists and teachers from the region around Philadelphia, he is responsible for a large set of standardized tests from which we learned much. Professor Hulsizer of the University of Illinois provided a teacher's guide to the test answers; and he and several others at Illinois and MIT have helped with test revisions. The Illinois group has taken the major part in development of detailed resource books for teachers, and in this they have been joined by the PSSC staff in Cambridge, who (with the usual aid from all sources) worked out both the student laboratory and the laboratory parts of the teacher's materials.

It is impossible for me to express my thanks adequately to those people whose continuing wisdom has been my chief reliance. The trouble—and pleasure—is that there are too many. Professor J. R. Zacharias has restrained himself with admirable control when, as often happened, the text or laboratory was not sufficiently settled to ease his job of making an accompanying film. He has encouraged us with his confidence despite the inevitable problems that arose in some of the new developments. Professors Morrison, Rogers, Frank, and Rossi have been among the major creators and selectors of material at every point. The whole process has been a continuing cycle and I can only stop where I began, by acknowledging our indebtedness to more people than I could make clear with ten times this space.

FRANCIS LEE FRIEDMAN
September 1960

THE SECOND edition, like its predecessor, is the fruit of the thought and effort of many people. It is impossible even to name the many persons—college and university professors, high school teachers, and high school students—who have contributed helpful criticisms and suggestions for revising the course. The members of the PSSC Steering Committee have taken an active role in evaluating these suggestions, generating new ideas, and approving the changes made for this edition. They are Judson B. Cross, Educational Services Incorporated; Frederick L. Ferris, Jr., Princeton University; Dr. Uri Haber-Schaim, Educational Services Incorporated; Ervin H. Hoffart, Educational Services Incorporated; Professor Robert I. Hulsizer, Jr., Massachusetts Institute of Technology; Professor Aaron Lemonick, Princeton University; Professor Philip Morrison, Massachusetts Institute of Technology; Professor Melba Phillips, University of Chicago; Professor Byron L. Youtz, Reed College; and Professor Jerrold R. Zacharias, Massachusetts Institute of Technology.

The complete rewriting of Chapter 31 and considerable revision of Chapter 30 were done by Professor Phillips and Professor Stefan Machlup of Western Reserve University. Helpful criticisms of their draft chapters and additional suggestions were contributed by Professors Anthony French of Massachusetts Institute of Technology and Arnold Arons of Amherst College.

Professor Philip Morrison was most helpful in reviewing the proposed changes for Part I of the text; he also contributed the essay on molecules and chemical structures at the end of Chapter 8. Professor Stephen Kline of Stanford University made many useful criticisms and suggestions on the treatment of the subject of heat and the conservation of energy.

The development by PSSC staff members of an effective, low-cost Millikan apparatus now allows the student to find his own evidence for the existence of the elementary charge instead of relying entirely on the film. Relevant portions of the text have been rewritten by Dr. Uri Haber-Schaim to take account of this new laboratory development.

The final choice of material for this edition was, of course, my responsibility.

In addition to Dr. Haber-Schaim, who has been a constant source of advice in all phases of this revision, I am indebted to many other members of the PSSC staff. Ervin H. Hoffart has collected and compiled feedback for the past six years and has distilled it into a form useful for the revision process. Judson B. Cross has again offered useful editorial advice on several chapters. Over the past several years a group of staff members have generated and tested new Home, Desk, and Lab problems. James Walter was particularly helpful in selecting and organizing the material for that all-important part of the text.

Paul Larkin has guided the many revisions of art work necessitated by pedagogic or artistic considerations. In this he was assisted by George Cope and his staff in the photographic studio of Educational Services Incorporated and by Dr. James Strickland of the movie studio, which generously supplied frames from existing films. John DeRoy of the PSSC shop lent his skill to setting up experiments and demonstrations for photographing. The lists of "Further Reading" at the ends of chapters have been expanded and brought up to date by a team of experienced high school teachers under the direction of Bruce Kingsbury.

As with all previous versions of this work, Benjamin T. Richards has assumed responsibility as production editor. For cooperation and assistance we are indebted to Louis Vogel and other members of the editorial and art departments of D. C. Heath and Company. Finally, I wish to acknowledge my indebtedness to my editorial assistant, Andrea Julian, whose sharp eye and understanding of physics have detected many lapses in consistency and clarity.

The fact that this course has been so widely and successfully used and has required so little real change in the revision is the highest possible tribute to the judgment and taste and insight of the man who, above all others, was responsible for the first edition: the late Francis Lee Friedman. It is my earnest hope that this edition has retained the spirit and the style which he established, while at the same time reflecting the light of experience and showing a sensitivity to the valid criticisms which we have received.

BYRON L. YOUTZ
July 1965

Contents

part I The Universe

The Universe

The Heart of a Galaxy: This photograph, taken with the 100-inch telescope at Mt. Wilson, shows the central region of the Great Galaxy in Andromeda, the sister to our own Milky Way system. If we could observe all that is taking place in such a galaxy, on successively smaller scales down to where we could perceive subatomic particles, we would find all of the principles of physics demonstrated.