

SECOND EDITION

*Fundamentals of Physics
and Applications*

HOWARD O. STEARNS

*Formerly Associate Professor of Physics
Simmons College, Boston*

New York, 1956

THE MACMILLAN COMPANY

© THE MACMILLAN COMPANY 1956

Published Simultaneously in Canada

All rights reserved—no part of this book may be reproduced in any form without permission in writing from the publisher, except by a reviewer who wishes to quote brief passages in connection with a review written for inclusion in magazine or newspaper.

First printing, September, 1956

First edition known as *Elementary Medical Physics*
(copyright 1947 by The Macmillan Company)

Printed in the United States of America

Library of Congress catalog card number: 56-7337

Preface to the Second Edition

A limited but clear understanding of the fundamentals of physics has become an absolute necessity for those working in the fields of medicine, optometry, nursing, physical therapy, the biological sciences, and related areas of endeavor. A knowledge of the functions of the human body, various medical instruments, and nuclear phenomena must of necessity be based upon an understanding of the application of physical principles to them.

Accordingly, this revised edition of *Fundamentals of Physics and Applications* is essentially a standard text in physics, with illustrative material drawn from the fields of the biological sciences and medicine. As in the first edition, emphasis has been placed on a simple and concise presentation of the subject matter. Several chapters have been rewritten for further simplification or to bring the discussion up to date, the most extensive revisions having been made in those concerning accelerated motion and nuclear phenomena. The former "Introduction," consisting of a brief review of mathematics, has been included as Appendix I; it is thus available in case of need but does not occupy as prominent a place as in the first edition. The new "Introduction" contains a very brief history of physics. A few errors, known to have existed in the first edition, have been corrected. New problems have been added to further emphasize the understanding of physical principles, and answers to all odd-numbered problems have been listed in Appendix IV.

The author again welcomes any suggestions for the improvement of the book from teachers or students.

Preface to the First Edition

For many years teachers in the various sciences have assumed that all that was required of them was to give the students a reasonably good experience in the fundamentals of a science, after which the students were expected to see how these applied to each new situation encountered. It has been the author's experience in teaching nurses and premedical-school students and in talking with medical-school graduates engaged in practice or research that they want to know the applications while they are studying the principles.

The foundation material of this book does not differ much from that of other elementary texts, for, after all, physics comprises a certain body of material that is essential to all sciences. The difference between this book and most others is in the effort the author has made to point out to the student where and how the laws and theories of physics are applied in the biological sciences or in the equipment and operation of a hospital.

Physics has been defined, rather too briefly, as the science of measurement. This is an important aspect of the subject that involves the use of numbers and units. Therefore, numerical problems have been included throughout most of the book. These give the student a better measure of his or her degree of understanding than do more general questions. There are, however, times when nonnumerical problems, which have been included in each chapter as study questions, require a more searching analysis of the fundamentals than numerical problems involving no more mental exercise than substituting numbers for letters in a formula. In both kinds of problems the author has attempted to make the understanding of principles more important than the facility in the arithmetical operations.

The author hopes the book will prove useful, and to that end he would greatly appreciate suggestions for improvement from those who use it either as teachers or as students.

Contents

PREFACE TO THE SECOND EDITION	iii
PREFACE TO THE FIRST EDITION	iv
INTRODUCTION: A BRIEF LOOK AT THE HISTORY OF PHYSICS	1

PART ONE: MECHANICS

1. UNITS AND MEASUREMENTS	9
The nature of measurement. A measurement includes a number and a unit. Fundamental and derived units. Difference between mass and weight. Standards. Metric and English units. Derived units. Some applications. The question of accuracy and precision. Relative importance of errors. Constant and accidental errors. Significant figures. Making measurements.	
2. VECTORS	17
Definition. Vector quantities. Force. Kinds of forces. Composition or addition of vectors. The equilibrant. Illustrative problems. Resolution of vectors. Torque and moment of force. Equilibrium of a rigid body. Center of gravity. Stability. Applications.	
3. FORCE AND MATTER	28
Newton's first law of motion. Newton's second law of motion. Force, mass, and acceleration. Acceleration due to gravity. Kinds of acceleration. Newton's third law. The universal nature of gravitation. The mass of the earth. Applications.	
4. WORK, POWER, FRICTION, EFFICIENCY	42
Definitions. Universal nature of energy. Transformations of energy. Kinds of energy. Energy units. Friction. Efficiency.	
5. SIMPLE MACHINES	49
Levers. The inclined plane. The screw. The pulley. Mechanical advantage. Applications. Magnitude of forces exerted by muscles.	

6. LIQUIDS	58
Force and pressure. The hydrostatic paradox. Equality of pressure in all directions. Pascal's principle. Pressure gauges. Density. Archimedes' principle. Specific gravity. Applications. Fluids in motion. Circulation. Some figures on heart action. The Bernoulli effect. Streamline flow.	
7. MOLECULAR PHYSICS	70
Molecular theory. Brownian movements. Pressure and diffusion of gases. Osmosis. Solution. Surface energy. Capillary action. Strength of materials. Adhesion and cohesion. Applications.	
8. GASES	80
Weight of the air. Pressure of the air. Boyle's law. Density of the air. Action of syringes and pumps. Siphons. Applications.	
PART TWO: HEAT	
9. THERMOMETRY AND EXPANSION	95
Heat and temperature. Thermometers. Thermometer scales. Linear expansion. Bimetallic strips. The volume expansion of solids. The expansion of liquids. The unusual expansion of water. Gas thermometers and the Kelvin scale of absolute temperature. The general gas law. Color changes. Thermostats.	
10. HEAT MEASUREMENT AND HEAT ENGINES	107
Quantity of heat. Calorimeters. Heat capacity; specific heat. Heat of combustion. The mechanical equivalent of heat. Heat engines. The gasoline engine. The diesel engine. Metabolism. Conditions affecting the metabolic rate. Total caloric requirement. Energy required for walking and studying. Body efficiency.	
11. HEAT TRANSFER	119
Conduction. Convection. Radiation. The electromagnetic spectrum. Effect of the surface on radiation. Evaporation. The Thermos bottle. Hot-water bottles. Radiant heat. Applications of "cold."	
12. CHANGE OF PHASE	127
The latent heat of fusion. Melting points. Change of volume during freezing. Effect of pressure on change of phase. Effect of dis-	

Contents

solved substances. Vaporization. Vapor pressure. Heat of vaporization. Sublimation. Sterilizers. Distillation. Humidity. Air conditioning. Air-conditioning equipment. Refrigeration. Mechanical refrigerators. The gas refrigerator. The weather, climate, and health. Physical factors affecting body temperature and comfort. Effects of weather and climate.

PART THREE: WAVE MOTION AND SOUND

13. VIBRATORY MOTION AND SOUND WAVES 147
Conditions for vibratory motion. Wave motion. Longitudinal waves. Transverse waves. Standing waves.
14. SOUND 153
Origin of sound. The speed of sound. The Doppler effect. Reflection. Refraction. Musical sounds and noise. Pitch. Loudness. Quality. Musical intervals and scales. Resonance. Acoustics.
15. THE EAR 162
Structure. The bel and decibel. Response at different frequencies. Audiometers and hearing aids. Binaural hearing.

PART FOUR: ELECTRICITY AND MAGNETISM

16. ELECTROSTATICS 169
Two kinds of charges. Electroscopes. Conductors and insulators. The unit charge. Electric field and potential. The electron theory. Explanation of electrification. Electrostatic induction. Charging an electroscope by induction. Capacitors. Discharge from points. The Van de Graaff x-ray generator. Other applications.
17. ELECTRIC CURRENTS 178
The voltaic cell. Potential. The Weston standard cell. The potentiometer. Effects of electric currents. Current. Ohm's law and resistance. The temperature coefficient of resistance. Ohm's law for a complete circuit. The Wheatstone bridge. Resistances in series and parallel. Applications.
18. CHEMICAL AND MAGNETIC EFFECTS OF AN ELECTRIC CURRENT 188
Chemical effects of an electric current. Electroplating. The storage battery. Faraday's laws of electrolysis. The coulomb. Hydrogen ion

measurements. Conductivity. Oersted's discovery. Ampère's rule. Lines of force. The action of a solenoid. Magnetic poles. Field strength and the unit pole. Magnetic induction. The earth as a magnet. The nature of magnetism. The galvanometer. The dc ammeter. The dc voltmeter.

19. ENERGY, HEAT, POWER, AND COST OF ELECTRICITY 202

The watt. The cost of electric energy. The heating effect. Other applications.

20. INDUCED CURRENTS 207

The production of an induced current. Lenz's law. The ac generator. The dc generator and motor. Magnitude of induced potentials. The induction coil. The transformer. Power transmission. Applications.

21. ELECTROMEDICAL APPARATUS 215

Essentials of an oscillating-current circuit. The Edison effect. The two-electrode tube. Other types of tubes. The electrocardiograph. Diathermy. Microwave diathermy. Electroencephalography. Bioelectric phenomena. Electric shock therapy. Electrosurgery. The electron microscope. The cathode-ray oscillograph.

PART FIVE: X-RAYS AND ATOMIC PHENOMENA

22. X-RAYS 233

The production of x-rays. X-ray tubes. The Coolidge tube. Accessory apparatus. Meters. Rectifying apparatus. Peak voltage and minimum wavelength. Nature of x-rays. Uses of fluorescent screens. Interaction of x-rays and matter. Reduction of scattered radiation. The film. Photofluorography. Body section radiography. Use of contrast media. Roentgen therapy. Measurement of radiation.

23. RADIUM AND ARTIFICIAL RADIOACTIVITY 254

Radium rays. Atomic structure. The periodic table. Atomic masses. Radioactive decay. The decay constant. Designation of isotopes. Radioactive series. Measurement of radioactivity. The atomic nucleus. Induced radioactivity. Nuclear reactions. Nuclear fission. The atom bomb. *Applications*: Astronomy. Botany. Chemistry. Engineering. Medicine. Archaeology. Geology.

PART SIX: LIGHT

24. PROPAGATION, ILLUMINATION, AND SOURCES	275
The speed of light. Light travels in straight lines. The inverse-square law. Measurement of illumination. Luminous flux. The legal definition of the lumen. Efficiency and cost. The photoelectric effect. Lighting. Standards of illumination. Sources of illumination in the hospital.	
25. REFLECTION OF LIGHT	284
Beams and rays. Regular and diffuse reflection. Laws of reflection. The plane mirror. The concave mirror. How to locate the image by construction. The mirror equation. The formation of a virtual image. Relative size of object and image. Convex mirror. The parabolic mirror.	
26. REFRACTION	291
The nature and cause of refraction. Total internal reflection. Refraction by a prism. Atmospheric refraction.	
27. LENSES	296
Spherical lenses. Focal length of a lens. Ray diagrams of lenses. The lens formula. The diopter. Lens defects. Spherical aberration. Chromatic aberration. Astigmatism.	
28. OPTICAL INSTRUMENTS	302
The simple magnifier. Lens combinations. The compound microscope. The numerical aperture. Magnifying power. Dark-field illumination. The photographic camera. The lens. The shutter. Film. The projection lantern. Motion pictures.	
29. SPECTRA AND COLOR	310
How a spectrum is formed. The cause of dispersion. The achromatic prism. The measurement of spectra. Types of spectra. Invisible spectra. The infrared region. The ultraviolet region. Mercury lamps. Fluorescence and phosphorescence. Color. Color temperature. Pigments and colors. Colorimeters. Color in the hospital.	

30. THE EYE	325
Structure. Optics of the eye. The cornea. Aqueous humor. The iris. The crystalline lens. Vitreous humor. The retina. Visual acuity. Spherical aberration. Chromatic aberration. Astigmatism. Refractive errors and their correction. Binocular vision. Color vision.	

31. INTERFERENCE, DIFFRACTION, AND POLARIZATION	336
Diffraction effects. Huygens' principle. Young's experiment. The diffraction grating. The color of thin films. Demonstration of the polarization of light. Polarizing materials. Polarimeters. Applications.	

APPENDIXES

I. A BRIEF REVIEW OF MATHEMATICS	347
II. USEFUL FORMULAE, EQUIVALENTS, CONVERSION FACTORS, TRIGONOMETRIC FUNCTIONS, FOUR-FIGURE LOGARITHMS	356
III. STATISTICAL DESCRIPTION OF FREQUENCY DISTRIBUTIONS	362
IV. ANSWERS TO ODD-NUMBERED PROBLEMS	367
INDEX	371

INTRODUCTION

A Brief Look at the History of Physics

Until as late as the latter part of the nineteenth century, physics was known as *natural philosophy*. It was part of the general field of philosophy, which included other subjects such as logic, metaphysics, epistemology, and ontology.

The earliest of the philosophers about whom definite records exist is **Thales of Miletus** (640–546 B.C.). He was acquainted with the action of magnets and of amber when rubbed with wool. He believed that both matter and electricity were atomic in nature.

Anaxagoras (500–428 B.C.) is credited with the view that the moon does not shine by its own light and that the moon is eclipsed because the earth shuts off the light of the sun.

Democritus (460–372 B.C.) was the first to state the atomic nature of matter definitely, though by a purely philosophical argument. He believed the creation of matter impossible since *nothing* was all that could be obtained from *nothing*.

Aristotle (384–322 B.C.), a pupil of the philosopher Plato, contributed extensively to all branches of knowledge: logic, rhetoric, metaphysics, psychology, and natural science. His intellectual brilliance and achievements in so many branches of learning exerted a profound influence among philosophers and theologians for hundreds of years.

Aristotle did occasionally draw on observed facts to substantiate his arguments. For example, he tried to show by abstract reasoning that the

earth was spherical, as shown by the shadow cast on the moon at the time of a lunar eclipse and also by the change in the altitude of the stars as one travels north or south. He is credited with maintaining that a heavier body falls faster than a lighter one; yet it is difficult to be sure from Aristotle's extant writings just what he held in regard to this point.¹

Aristotle believed the earth to be the center of the universe, with the sun, moon, planets, and stars revolving about the earth in concentric spheres. His authority was so generally recognized that the brilliant work of Aristarchus in the following century was not given the credit it deserved.

Aristarchus of Samos (about 310–230 B.C.) developed a theory of the universe which was the same as that proposed by Copernicus 2000 years later.

Archimedes (287–212 B.C.) is known to all students of elementary physics for the principle in hydrostatics which bears his name.

A long gap appears in almost all histories of science from soon after the beginning of the Christian Era to the time of Galileo Galilei. During this interval most Christian philosophers were theologians more concerned with the Second Coming than with problems of the world around them. About the eighth century the Arabs translated many Greek writings into Arabic.

Leonardo da Vinci (1452–1519) was an Italian painter, architect, sculptor, engineer, and philosopher. He made extensive studies of the flight of birds with the idea of developing some kind of a flying machine.² He also attacked problems in mechanics and dynamics. For example, on the subject of perpetual motion he wrote: "Oh speculators on perpetual motion, how many vain projects of the like character you have created. Go and be the companions of the searchers after gold!"³

Da Vinci's writings created less opposition than those of Galileo and Copernicus, who followed him, because they were left in manuscript form and he did not teach in any of the universities. For this reason he exerted very little influence on science of his time; in fact, it is only in recent years that his scientific ideas have received the credit they deserve.

Copernicus (1473–1543), a mathematician and astronomer, perceived a simplified solar system with the sun at the center to displace the Ptolemaic system of an earth-centered universe. Ptolemy (about A.D. 127–

¹ Richtmyer, F. K.; Kennard, E. H.; and Lauritsen, T.: *Introduction to Modern Physics*, 5th ed. McGraw-Hill Book Company, New York, 1955, p. 8.

² Hart, I. B.: *The Mechanical Investigations of Leonardo da Vinci*. Chapman & Hall, Ltd., London, 1925. Chap. VII.

³ *Ibid.*, p. 95.

151) had developed a complicated structure of deferents and epicycles. As better observations were made, the epicycles were complicated by adding epicycles to epicycles until each planet was provided with from forty to sixty epicycles turning one upon another.⁴

Because the theories proposed by Copernicus were so revolutionary and contrary to the accepted theories taught by the theologians of his time, he refrained from having them published until the close of his life.

Galileo Galilei (1564–1642) is generally considered to be the first to adopt the methods of modern science. He excelled in the classics and literature as a young student. He later studied medicine at the University of Pisa. It was here that he made his first discovery concerning the uniformity of oscillation of a pendulum. He checked the period of the swinging of a hanging lamp by comparing it with his pulse. He found the period of oscillation stayed the same even though the amplitude of the swings became less.

He abandoned the study of medicine for his interest in mathematics and at the age of twenty-six became professor of mathematics at Pisa. While there he is supposed to have performed his famous experiment of dropping dissimilar weights simultaneously from the leaning tower. He did this to show that the heavier weight did not travel faster. Forced to leave Pisa, in 1592 he became professor of mathematics at the University of Padua.

In 1610 Galileo invented a telescope with a power of 30 diameters. With this he discovered four of the satellites of Jupiter. He made numerous other astronomical discoveries, all of which tended to support the hated Copernican theory. Because of this and some of his later writings he was called before the Inquisition. At that time he was old, impaired in health and spirit, so he expressed his willingness to “abjure, curse, and detest” his heresies. His work in mechanics aided Newton to state his three laws of motion. Galileo died the year that Newton was born.

In the period just before the time of Newton came such men as **Snell** (1591–1626), who discovered the true law of refraction; **Torricelli** (1608–1647), who discovered the principle of the barometer and the variation of barometric pressure with altitude; and **Pascal** (1623–1662), who explained the variation of pressure with altitude and later announced the principle of the transmission of pressure in a confined fluid (known as Pascal’s principle).

Sir Isaac Newton (1642–1727) was born on Christmas Day in 1642 in Woolsthorpe. After an unsatisfactory early school experience he sud-

⁴ Baker, R. H.: *An Introduction to Astronomy*, 4th ed. D. Van Nostrand Company, Inc., New York, 1952, p. 150.

denly exhibited a remarkable aptitude for mathematics. He worked hard to prepare himself for Trinity College, Cambridge. While still in his twenties he had developed differential calculus, perfected the reflecting telescope, discovered the law of universal gravitation, and had to his credit a host of other less-well-known achievements. At the age of twenty-six he was appointed to the professorship of mathematics at Cambridge University. He was truly a "giant among giants."⁵

Newton would be famous for almost any one of the many investigations he conducted. His work on optics was monumental, yet he failed to detect two flaws in his theories. One was that dispersion of light was proportional to refraction, and the other was that light must consist of particles in order to account for the straight-line propagation. It was not until 1730 that achromatic lenses were first made.

His famous *Principia*, published in 1697, was "without exception the most important work in natural philosophy extant."⁶ "In this treatise the famous three laws of motion are assumed as axioms."⁷

The eighteenth century witnessed many additional contributions to an understanding of the material world. **Bernoulli** (1700–1782) made many discoveries in hydrodynamics; **Euler** and **Lagrange** developed mathematical tools for the solution of many problems. The aberration of light was discovered by **Bradley** in 1728. **Du Fay**, **Benjamin Franklin**, **Cavendish**, and **Coulomb** discovered many of the fundamental facts about electricity, with **Ampère**, **Oersted**, and **Faraday** discovering the relationship between electricity and magnetism.

The nineteenth century was a period of such extensive progress that it would take most of the rest of this book to describe only a part of it. The law of the conservation of energy was announced during this century. The first qualitative experiment bearing on the nature of heat was performed by **Count Rumford**, an American who was opposed to the Revolution and fled to England; from there he went to Bavaria where his famous experiments were carried out. **Joule** (1818–1889) measured quantitatively the equivalence of heat and energy.

The revival of the wave theory of light on the basis of the experiments of **Thomas Young** (1773–1829) led to the abandonment of Newton's corpuscular theory. Other researches in light were carried on by **Fraunhofer**, **Doppler**, **Kirckhoff**, and **Bunsen**. Maxwell developed the mathematical foundation for the electromagnetic theory.

⁵ Hart, I. B.: *Makers of Science*. Oxford University Press, London, 1924, p. 140.

⁶ *Ibid.*, p. 162.

⁷ Richtmyer, F. K.; Kennard, E. H.; and Lauritsen, T.: *Op. cit.*, p. 26.

In the field of electricity **Michael Faraday** and **Sir Humphry Davy** developed the relations between electricity, magnetism, and the chemical effects of an electric current.

In this country the work of **Joseph Henry** on electromagnets led to the invention of the telegraph.

James Clerk Maxwell (1831–1879) was one of the greatest mathematical physicists of the nineteenth century. His papers cover three main fields: color vision, molecular theory, and electromagnetic theory. In the latter theory he utilized displacement currents in the dielectric field surrounding charges to account for the propagation of an electromagnetic disturbance. His *Treatise on Electricity and Magnetism*, published in 1873, ranks in importance with Newton's *Principia*.

Hermann L. F. von Helmholtz (1821–1894) is the outstanding contributor to medical physics during the nineteenth century. He was descended on his mother's side from William Penn. His first training was as a surgeon in the Prussian army. At the age of 21 he wrote a thesis on his discovery of nerve cells in ganglia. He was professor of physiology first at Königsberg, then at Bonn, and later at Heidelberg. In 1871 he became professor of physics at Berlin. His investigations covered almost the whole field of science—physiology, physiological optics, physiological acoustics, chemistry, mathematics, electricity and magnetism, and theoretical mechanics. In 1847 he read a paper on *The Conservation of Force* which made him one of the founders of our generally accepted law of the conservation of energy. His two great works, *Physiological Optics* (which appeared in 1856) and *Sensations of Tone* (published in 1862), are still authoritative in many respects.

Twentieth century physics really started shortly before the century began. In 1895 **Wilhelm K. Roentgen** discovered x-rays. This discovery was followed by the work of **Becquerel** and the **Curies** on radioactivity. The behavior and nature of electrons were studied by **Sir J. J. Thomson** and his associates in England, while in this country **R. A. Millikan** measured the charge on the electron in his famous oil-drop experiment. **F. W. Aston** in England and **A. J. Dempster** in this country made accurate measurements of atomic masses which led directly to the discovery of a host of isotopes.

About the beginning of the century **Max Planck**, in attempting to explain the radiation of light from a black body, supposed the energy to be emitted in tiny packets of energy called quanta. This led through the experimental and mathematical researches of **Bohr**, **Einstein**, **de Broglie**, **Schrödinger**, and **Heisenberg** to the modern quantum mechanics,

a domain in which mathematical equations have displaced physical models of the interaction of matter and energy.

The more recent developments of twentieth century physics deal with nuclear phenomena such as cosmic rays, nucleons, and nucleonics. Our knowledge of cosmic rays was expanded by the studies of **R. A. Millikan**, **C. D. Anderson**, and **A. H. Compton**. Nuclear theories were advanced by the work of men like **H. Yukawa**, **H. A. Bethe**, and **J. R. Oppenheimer**. Atomic fission was discovered in Germany by **L. Meitner** and **O. Hahn**. Experiments on atomic nuclei were carried on in this country by **E. Fermi**, **E. O. Lawrence**, **G. T. Seaborg**, and many others.

A glance at the table of contents of any recent number of the *Physical Review* will show the diversity of problems being studied and the number of people who are studying them.