

经典电动力学

第三版
影印版

Classical Electrodynamics

Third Edition

John David Jackson

Professor Emeritus of Physics
University of California, Berkeley



高等教育出版社



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内 容 提 要

本书是一本有着很高知名度的电动力学教材,长期以来被世界上多所大学选用。本影印版是2001年出版的第三版。与前两版相比,第三版在保留基本经典电动力学内容的基础上,做了不少调整。如增加了一些关于数字计算方面的内容;删除了等离子体一章,将其部分内容在其它章节体现;增加了一些新的科技发展内容,如光纤、半导体波导管、同步辐射等。

全书共分12章,可作为物理类专业电动力学课程的教材,尤其适合开展双语教学的学校,对于有志出国深造的人员也是一本必不可少的参考书。

**To the memory of my father,
Walter David Jackson**

Preface

It has been 36 years since the appearance of the first edition of this book, and 23 years since the second. Such intervals may be appropriate for a subject whose fundamental basis was completely established theoretically 134 years ago by Maxwell and experimentally 110 years ago by Hertz. Still, there are changes in emphasis and applications. This third edition attempts to address both without any significant increase in size. Inevitably, some topics present in the second edition had to be eliminated to make room for new material. One major omission is the chapter on plasma physics, although some pieces appear elsewhere. Readers who miss particular topics may, I hope, be able to avail themselves of the second edition.

The most visible change is the use of SI units in the first 10 chapters. Gaussian units are retained in the later chapters, since such units seem more suited to relativity and relativistic electrodynamics than SI. As a reminder of the system of units being employed, the running head on each left-hand page carries “—SI” or “—G” depending on the chapter.

My tardy adoption of the universally accepted SI system is a recognition that almost all undergraduate physics texts, as well as engineering books at all levels, employ SI units throughout. For many years Ed Purcell and I had a pact to support each other in the use of Gaussian units. Now I have betrayed him! Although this book is formally dedicated to the memory of my father, I dedicate this third edition informally to the memory of Edward Mills Purcell (1912–1997), a marvelous physicist with deep understanding, a great teacher, and a wonderful man.

Because of the increasing use of personal computers to supplement analytical work or to attack problems not amenable to analytic solution, I have included some new sections on the *principles* of some numerical techniques for electrostatics and magnetostatics, as well as some elementary problems. Instructors may use their ingenuity to create more challenging ones. The aim is to provide an understanding of such methods before blindly using canned software or even *Mathematica* or *Maple*.

There has been some rearrangement of topics—Faraday’s law and quasi-static fields are now in Chapter 5 with magnetostatics, permitting a more logical discussion of energy and inductances. Another major change is the consolidation of the discussion of radiation by charge-current sources, in both elementary and exact multipole forms, in Chapter 9. All the applications to scattering and diffraction are in Chapter 10.

The principles of optical fibers and dielectric waveguides are discussed in two new sections in Chapter 8. In Chapter 13 the treatment of energy loss has been shortened and strengthened. Because of the increasing importance of synchrotron radiation as a research tool, the discussion in Chapter 14 has been augmented by a detailed section on the physics of wigglers and undulators for synchrotron light sources. There is new material in Chapter 16 on radiation reaction and models of classical charged particles, as well as changed emphasis.

There is much tweaking by small amounts throughout. I hope the reader will

not notice, or will notice only greater clarity. To mention but a few minor additions: estimating self-inductances, Poynting's theorem in lossy materials, polarization potentials (Hertz vectors), Goos-Hänchen effect, attenuation in optical fibers, London penetration depth in superconductors. And more problems, of course! Over 110 new problems, a 40% increase, all aimed at educating, not discouraging.

In preparing this new edition and making corrections, I have benefited from questions, suggestions, criticism, and advice from many students, colleagues, and newfound friends. I am in debt to all. Particular thanks for help in various ways go to Myron Bander, David F. Bartlett, Robert N. Cahn, John Cooper, John L. Gammel, David J. Griffiths, Leroy T. Kerth, Kwang J. Kim, Norman M. Kroll, Michael A. Lee, Harry J. Lipkin, William Mendoza, Gerald A. Miller, William A. Newcomb, Ivan Otero, Alan M. Portis, Fritz Rohrlich, Wayne M. Saslow, Chris Schmid, Kevin E. Schmidt, and George H. Trilling.

J. David Jackson

Berkeley, California, 1998, 2001

Preface to the Second Edition

In the thirteen years since the appearance of the first edition, my interest in classical electromagnetism has waxed and waned, but never fallen to zero. The subject is ever fresh. There are always important new applications and examples. The present edition reflects two efforts on my part: the refinement and improvement of material already in the first edition; the addition of new topics (and the omission of a few).

The major purposes and emphasis are still the same, but there are extensive changes and additions. A major augmentation is the "Introduction and Survey" at the beginning. Topics such as the present experimental limits on the mass of the photon and the status of linear superposition are treated there. The aim is to provide a survey of those basics that are often assumed to be well known when one writes down the Maxwell equations and begins to solve specific examples. Other major changes in the first half of the book include a new treatment of the derivation of the equations of macroscopic electromagnetism from the microscopic description; a discussion of symmetry properties of mechanical and electromagnetic quantities; sections on magnetic monopoles and the quantization condition of Dirac; Stokes's polarization parameters; a unified discussion of the frequency dispersion characteristics of dielectrics, conductors, and plasmas; a discussion of causality and the Kramers-Kronig dispersion relations; a simplified, but still extensive, version of the classic Sommerfeld-Brillouin problem of the arrival of a signal in a dispersive medium (recently verified experimentally); an unusual example of a resonant cavity; the normal-mode expansion of an arbitrary field in a wave guide; and related discussions of sources in a guide or cavity and the transmission and reflection coefficients of flat obstacles in wave guides.

Chapter 9, on simple radiating systems and diffraction, has been enlarged to include scattering at long wavelengths (the blue sky, for example) and the optical theorem. The sections on scalar and vectorial diffraction have been improved.

Chapters 11 and 12, on special relativity, have been rewritten almost completely. The old pseudo-Euclidean metric with $x_4 = ict$ has been replaced by $g^{\mu\nu}$ (with $g^{00} = +1$, $g^{ii} = -1$, $i = 1, 2, 3$). The change of metric necessitated a complete revision and thus permitted substitution of modern experiments and concerns about the experimental basis of the special theory for the time-honored aberration of starlight and the Michelson-Morley experiment. Other aspects have been modernized, too. The extensive treatment of relativistic kinematics of the first edition has been relegated to the problems. In its stead is a discussion of the Lagrangian for the electromagnetic fields, the canonical and symmetric stress-energy tensor, and the Proca Lagrangian for massive photons.

Significant alterations in the remaining chapters include a new section on transition radiation, a completely revised (and much more satisfactory) semi-classical treatment of radiation emitted in collisions that stresses momentum transfer instead of impact parameter, and a better derivation of the coupling of multipole fields to their sources. The collection of formulas and page references to special functions on the front and back flyleaves is a much requested addition. Of the 278 problems, 117 (more than 40 per cent) are new.

The one area that remains almost completely unchanged is the chapter on magnetohydrodynamics and plasma physics. I regret this. But the book obviously has grown tremendously, and there are available many books devoted exclusively to the subject of plasmas or magnetohydrodynamics.

Of minor note is the change from Maxwell's equations and a Green's function to the Maxwell equations and a Green function. The latter boggles some minds, but is in conformity with other usage (Bessel function, for example). It is still Green's theorem, however, because that's whose theorem it is.

Work on this edition began in earnest during the first half of 1970 on the occasion of a sabbatical leave spent at Clare Hall and the Cavendish Laboratory in Cambridge. I am grateful to the University of California for the leave and indebted to N. F. Mott for welcoming me as a visitor to the Cavendish Laboratory and to R. J. Eden and A. B. Pippard for my appointment as a Visiting Fellow of Clare Hall. Tangible and intangible evidence at the Cavendish of Maxwell, Rayleigh and Thomson provided inspiration for my task; the stimulation of everyday activities there provided necessary diversion.

This new edition has benefited from questions, suggestions, comments and criticism from many students, colleagues, and strangers. Among those to whom I owe some specific debt of gratitude are A. M. Bincer, L. S. Brown, R. W. Brown, E. U. Condon, H. H. Denman, S. Deser, A. J. Dragt, V. L. Fitch, M. B. Halpern, A. Hobson, J. P. Hurley, D. L. Judd, L. T. Kerth, E. Marx, M. Nauenberg, A. B. Pippard, A. M. Portis, R. K. Sachs, W. M. Saslow, R. Schleif, V. L. Telegdi, T. Tredon, E. P. Tryon, V. F. Weisskopf, and Dudley Williams. Especially helpful were D. G. Boulware, R. N. Cahn, Leverett Davis, Jr., K. Gottfried, C. K. Graham, E. M. Purcell, and E. H. Wichmann. I send my thanks and fraternal greetings to all of these people, to the other readers who have written to me, and the countless students who have struggled with the problems (and sometimes written asking for solutions to be dispatched before some deadline!). To my mind, the book is better than ever. May each reader benefit and enjoy!

J. D. Jackson

Berkeley, California, 1974

Preface to the First Edition

Classical electromagnetic theory, together with classical and quantum mechanics, forms the core of present-day theoretical training for undergraduate and graduate physicists. A thorough grounding in these subjects is a requirement for more advanced or specialized training.

Typically the undergraduate program in electricity and magnetism involves two or perhaps three semesters beyond elementary physics, with the emphasis on the fundamental laws, laboratory verification and elaboration of their consequences, circuit analysis, simple wave phenomena, and radiation. The mathematical tools utilized include vector calculus, ordinary differential equations with constant coefficients, Fourier series, and perhaps Fourier or Laplace transforms, partial differential equations, Legendre polynomials, and Bessel functions.

As a general rule, a two-semester course in electromagnetic theory is given to beginning graduate students. It is for such a course that my book is designed. My aim in teaching a graduate course in electromagnetism is at least threefold. The first aim is to present the basic subject matter as a coherent whole, with emphasis on the unity of electric and magnetic phenomena, both in their physical basis and in the mode of mathematical description. The second, concurrent aim is to develop and utilize a number of topics in mathematical physics which are useful in both electromagnetic theory and wave mechanics. These include Green's theorems and Green's functions, orthonormal expansions, spherical harmonics, cylindrical and spherical Bessel functions. A third and perhaps most important purpose is the presentation of new material, especially on the interaction of relativistic charged particles with electromagnetic fields. In this last area personal preferences and prejudices enter strongly. My choice of topics is governed by what I feel is important and useful for students interested in theoretical physics, experimental nuclear and high-energy physics, and that as yet ill-defined field of plasma physics.

The book begins in the traditional manner with electrostatics. The first six chapters are devoted to the development of Maxwell's theory of electromagnetism. Much of the necessary mathematical apparatus is constructed along the way, especially in Chapter 2 and 3, where boundary-value problems are discussed thoroughly. The treatment is initially in terms of the electric field E and the magnetic induction B , with the derived macroscopic quantities, D and H , introduced by suitable averaging over ensembles of atoms or molecules. In the discussion of dielectrics, simple classical models for atomic polarizability are described, but for magnetic materials no such attempt is made. Partly this omission was a question of space, but truly classical models of magnetic susceptibility are not possible. Furthermore, elucidation of the interesting phenomenon of ferromagnetism needs almost a book in itself.

The next three chapters (7–9) illustrate various electromagnetic phenomena, mostly of a macroscopic sort. Plane waves in different media, including plasmas as well as dispersion and the propagation of pulses, are treated in Chapter 7. The discussion of wave guides and cavities in Chapter 8 is developed for systems of arbitrary cross section, and the problems of attenuation in guides and the Q of

a cavity are handled in a very general way which emphasizes the physical processes involved. The elementary theory of multipole radiation from a localized source and diffraction occupy Chapter 9. Since the simple scalar theory of diffraction is covered in many optics textbooks, as well as undergraduate books on electricity and magnetism, I have presented an improved, although still approximate, theory of diffraction based on vector rather than scalar Green's theorems.

The subject of magnetohydrodynamics and plasmas receives increasingly more attention from physicists and astrophysicists. Chapter 10 represents a survey of this complex field with an introduction to the main physical ideas involved.

The first nine or ten chapters constitute the basic material of classical electricity and magnetism. A graduate student in physics may be expected to have been exposed to much of this material, perhaps at a somewhat lower level, as an undergraduate. But he obtains a more mature view of it, understands it more deeply, and gains a considerable technical ability in analytic methods of solution when he studies the subject at the level of this book. He is then prepared to go on to more advanced topics. The advanced topics presented here are predominantly those involving the interaction of charged particles with each other and with electromagnetic fields, especially when moving relativistically.

The special theory of relativity had its origins in classical electrodynamics. And even after almost 60 years, classical electrodynamics still impresses and delights as a beautiful example of the covariance of physical laws under Lorentz transformations. The special theory of relativity is discussed in Chapter 11, where all the necessary formal apparatus is developed, various kinematic consequences are explored, and the covariance of electrodynamics is established. The next chapter is devoted to relativistic particle kinematics and dynamics. Although the dynamics of charged particles in electromagnetic fields can properly be considered electrodynamics, the reader may wonder whether such things as kinematic transformations of collision problems can. My reply is that these examples occur naturally once one has established the four-vector character of a particle's momentum and energy, that they serve as useful practice in manipulating Lorentz transformations, and that the end results are valuable and often hard to find elsewhere.

Chapter 13 on collisions between charged particles emphasizes energy loss and scattering and develops concepts of use in later chapters. Here for the first time in the book I use semiclassical arguments based on the uncertainty principle to obtain approximate quantum-mechanical expressions for energy loss, etc., from the classical results. This approach, so fruitful in the hands of Niels Bohr and E. J. Williams, allows one to see clearly how and when quantum-mechanical effects enter to modify classical considerations.

The important subject of emission of radiation by accelerated point charges is discussed in detail in Chapters 14 and 15. Relativistic effects are stressed, and expressions for the frequency and angular dependence of the emitted radiation are developed in sufficient generality for all applications. The examples treated range from synchrotron radiation to bremsstrahlung and radiative beta processes. Cherenkov radiation and the Weizsäcker-Williams method of virtual quanta are also discussed. In the atomic and nuclear collision processes semiclassical arguments are again employed to obtain approximate quantum-mechanical results. I lay considerable stress on this point because I feel that it is important for the student to see that radiative effects such as bremsstrahlung are almost entirely

classical in nature, even though involving small-scale collisions. A student who meets *bremsstrahlung* for the first time as an example of a calculation in quantum field theory will not understand its physical basis.

Multipole fields form the subject matter of Chapter 16. The expansion of scalar and vector fields in spherical waves is developed from first principles with no restrictions as to the relative dimensions of source and wavelength. Then the properties of electric and magnetic multipole radiation fields are considered. Once the connection to the multiple moments of the source has been made, examples of atomic and nuclear multipole radiation are discussed, as well as a macroscopic source whose dimensions are comparable to a wavelength. The scattering of a plane electromagnetic wave by a spherical object is treated in some detail in order to illustrate a boundary-value problem with vector spherical waves.

In the last chapter the difficult problem of radiative reaction is discussed. The treatment is physical, rather than mathematical, with the emphasis on delimiting the areas where approximate radiative corrections are adequate and on finding where and why existing theories fail. The original Abraham-Lorentz theory of the self-force is presented, as well as more recent classical considerations.

The book ends with an appendix on units and dimensions and a bibliography. In the appendix I have attempted to show the logical steps involved in setting up a system of units, without haranguing the reader as to the obvious virtues of *my* choice of units. I have provided two tables which I hope will be useful, one for converting equations and symbols and the other for converting a given quantity of something from so many Gaussian units to so many mks units, and vice versa. The bibliography lists books which I think the reader may find pertinent and useful for reference or additional study. These books are referred to by author's name in the reading lists at the end of each chapter.

This book is the outgrowth of a graduate course in classical electrodynamics which I have taught off and on over the past eleven years, at both the University of Illinois and McGill University. I wish to thank my colleagues and students at both institutions for countless helpful remarks and discussions. Special mention must be made of Professor P. R. Wallace of McGill, who gave me the opportunity and encouragement to teach what was then a rather unorthodox course in electromagnetism, and Professors H. W. Wyld and G. Ascoli of Illinois, who have been particularly free with many helpful suggestions on the treatment of various topics. My thanks are also extended to Dr. A. N. Kaufman for reading and commenting on a preliminary version of the manuscript, and to Mr. G. L. Kane for his zealous help in preparing the index.

J. D. Jackson

Urbana, Illinois, January, 1962

Contents

Introduction and Survey **1**

1.1	Maxwell Equations in Vacuum, Fields, and Sources	2
1.2	Inverse Square Law, or the Mass of the Photon	5
1.3	Linear Superposition	9
1.4	Maxwell Equations in Macroscopic Media	13
1.5	Boundary Conditions at Interfaces Between Different Media	16
1.6	Some Remarks on Idealizations in Electromagnetism	19
	<i>References and Suggested Reading</i>	22

Chapter 1 / Introduction to Electrostatics **24**

1.1	Coulomb's Law	24
1.2	Electric Field	24
1.3	Gauss's Law	27
1.4	Differential Form of Gauss's Law	28
1.5	Another Equation of Electrostatics and the Scalar Potential	29
1.6	Surface Distributions of Charges and Dipoles and Discontinuities in the Electric Field and Potential	31
1.7	Poisson and Laplace Equations	34
1.8	Green's Theorem	35
1.9	Uniqueness of the Solution with Dirichlet or Neumann Boundary Conditions	37
1.10	Formal Solution of Electrostatic Boundary-Value Problem with Green Function	38
1.11	Electrostatic Potential Energy and Energy Density; Capacitance	40
1.12	Variational Approach to the Solution of the Laplace and Poisson Equations	43
1.13	Relaxation Method for Two-Dimensional Electrostatic Problems	47
	<i>References and Suggested Reading</i>	50
	<i>Problems</i>	50

Chapter 2 / Boundary-Value Problems in Electrostatics: I **57**

2.1	Method of Images	57
2.2	Point Charge in the Presence of a Grounded Conducting Sphere	58
2.3	Point Charge in the Presence of a Charged, Insulated, Conducting Sphere	60
2.4	Point Charge Near a Conducting Sphere at Fixed Potential	61
2.5	Conducting Sphere in a Uniform Electric Field by Method of Images	62
2.6	Green Function for the Sphere; General Solution for the Potential	64
2.7	Conducting Sphere with Hemispheres at Different Potentials	65

2.8	Orthogonal Functions and Expansions	67
2.9	Separation of Variables; Laplace Equation in Rectangular Coordinates	70
2.10	A Two-Dimensional Potential Problem; Summation of Fourier Series	72
2.11	Fields and Charge Densities in Two-Dimensional Corners and Along Edges	75
2.12	Introduction to Finite Element Analysis for Electrostatics	79
	<i>References and Suggested Reading</i>	84
	<i>Problems</i>	85

Chapter 3 / Boundary-Value Problems in Electrostatics: II **95**

3.1	Laplace Equation in Spherical Coordinates	95
3.2	Legendre Equation and Legendre Polynomials	96
3.3	Boundary-Value Problems with Azimuthal Symmetry	101
3.4	Behavior of Fields in a Conical Hole or Near a Sharp Point	104
3.5	Associated Legendre Functions and the Spherical Harmonics $Y_{lm}(\theta, \phi)$	107
3.6	Addition Theorem for Spherical Harmonics	110
3.7	Laplace Equation in Cylindrical Coordinates; Bessel Functions	111
3.8	Boundary-Value Problems in Cylindrical Coordinates	117
3.9	Expansion of Green Functions in Spherical Coordinates	119
3.10	Solution of Potential Problems with the Spherical Green Function Expansion	112
3.11	Expansion of Green Functions in Cylindrical Coordinates	125
3.12	Eigenfunction Expansions for Green Functions	127
3.13	Mixed Boundary Conditions, Conducting Plane with a Circular Hole	129
	<i>References and Suggested Reading</i>	135
	<i>Problems</i>	135

Chapter 4 / Multipoles, Electrostatics of Macroscopic Media, Dielectrics **145**

4.1	Multipole Expansion	145
4.2	Multipole Expansion of the Energy of a Charge Distribution in an External Field	150
4.3	Elementary Treatment of Electrostatics with Ponderable Media	151
4.4	Boundary-Value Problems with Dielectrics	154
4.5	Molecular Polarizability and Electric Susceptibility	159
4.6	Models for Electric Polarizability	162
4.7	Electrostatic Energy in Dielectric Media	165
	<i>References and Suggested Reading</i>	169
	<i>Problems</i>	169

Chapter 5 / Magnetostatics, Faraday's Law, Quasi-Static Fields **174**

5.1	Introduction and Definitions	174
5.2	Biot and Savart Law	175

5.3	Differential Equations of Magnetostatics and Ampère's Law	178
5.4	Vector Potential	180
5.5	Vector Potential and Magnetic Induction for a Circular Current Loop	181
5.6	Magnetic Fields of a Localized Current Distribution, Magnetic Moment	184
5.7	Force and Torque on and Energy of a Localized Current Distribution in an External Magnetic Induction	188
5.8	Macroscopic Equations, Boundary Conditions on \mathbf{B} and \mathbf{H}	191
5.9	Methods of Solving Boundary-Value Problems in Magnetostatics	194
5.10	Uniformly Magnetized Sphere	198
5.11	Magnetized Sphere in an External Field; Permanent Magnets	199
5.12	Magnetic Shielding, Spherical Shell of Permeable Material in a Uniform Field	201
5.13	Effect of a Circular Hole in a Perfectly Conducting Plane with an Asymptotically Uniform Tangential Magnetic Field on One Side	203
5.14	Numerical Methods for Two-Dimensional Magnetic Fields	206
5.15	Faraday's Law of Induction	208
5.16	Energy in the Magnetic Field	212
5.17	Energy and Self- and Mutual Inductances	215
5.18	Quasi-Static Magnetic Fields in Conductors; Eddy Currents; Magnetic Diffusion	218
	<i>References and Suggested Reading</i>	223
	<i>Problems</i>	225

Chapter 6 / Maxwell Equations, Macroscopic Electromagnetism, Conservation Laws

237

6.1	Maxwell's Displacement Current; Maxwell Equations	237
6.2	Vector and Scalar Potentials	239
6.3	Gauge Transformations, Lorenz Gauge, Coulomb Gauge	240
6.4	Green Functions for the Wave Equation	243
6.5	Retarded Solutions for the Fields: Jefimenko's Generalizations of the Coulomb and Biot-Savart Laws; Heaviside-Feynman Expressions for Fields of Point Charge	246
6.6	Derivation of the Equations of Macroscopic Electromagnetism	248
6.7	Poynting's Theorem and Conservation of Energy and Momentum for a System of Charged Particles and Electromagnetic Fields	258
6.8	Poynting's Theorem in Linear Dissipative Media with Losses	262
6.9	Poynting's Theorem for Harmonic Fields; Field Definitions of Impedance and Admittance	264
6.10	Transformation Properties of Electromagnetic Fields and Sources Under Rotations, Spatial Reflections, and Time Reversal	267
6.11	On the Question of Magnetic Monopoles	273
6.12	Discussion of the Dirac Quantization Condition	275
6.13	Polarization Potentials (Hertz Vectors)	280
	<i>References and Suggested Reading</i>	282
	<i>Problems</i>	283

Chapter 7 / Plane Electromagnetic Waves and Wave Propagation 295

7.1	Plane Waves in a Nonconducting Medium	295
7.2	Linear and Circular Polarization; Stokes Parameters	299
7.3	Reflection and Refraction of Electromagnetic Waves at a Plane Interface Between Two Dielectrics	302
7.4	Polarization by Reflection, Total Internal Reflection; Goos–Hänchen Effect	306
7.5	Frequency Dispersion Characteristics of Dielectrics, Conductors, and Plasmas	309
7.6	Simplified Model of Propagation in the Ionosphere and Magnetosphere	316
7.7	Magnetohydrodynamic Waves	319
7.8	Superposition of Waves in One Dimension; Group Velocity	322
7.9	Illustration of the Spreading of a Pulse As It Propagates in a Dispersive Medium	326
7.10	Causality in the Connection Between D and E ; Kramers–Kronig Relations	330
7.11	Arrival of a Signal After Propagation Through a Dispersive Medium	335
	<i>References and Suggested Reading</i>	339
	<i>Problems</i>	340

Chapter 8 / Waveguides, Resonant Cavities, and Optical Fibers 352

8.1	Fields at the Surface of and Within a Conductor	352
8.2	Cylindrical Cavities and Waveguides	356
8.3	Waveguides	359
8.4	Modes in a Rectangular Waveguide	361
8.5	Energy Flow and Attenuation in Waveguides	363
8.6	Perturbation of Boundary Conditions	366
8.7	Resonant Cavities	368
8.8	Power Losses in a Cavity; Q of a Cavity	371
8.9	Earth and Ionosphere as a Resonant Cavity: Schumann Resonances	374
8.10	Multimode Propagation in Optical Fibers	378
8.11	Modes in Dielectric Waveguides	385
8.12	Expansion in Normal Modes; Fields Generated by a Localized Source in a Hollow Metallic Guide	389
	<i>References and Suggested Reading</i>	395
	<i>Problems</i>	396

Chapter 9 / Radiating Systems, Multipole Fields and Radiation 407

9.1	Fields and Radiation of a Localized Oscillating Source	407
9.2	Electric Dipole Fields and Radiation	410
9.3	Magnetic Dipole and Electric Quadrupole Fields	413
9.4	Center-Fed Linear Antenna	416
9.5	Multipole Expansion for Localized Source or Aperture in Waveguide	419

9.6	Spherical Wave Solutions of the Scalar Wave Equation	425
9.7	Multipole Expansion of the Electromagnetic Fields	429
9.8	Properties of Multipole Fields, Energy and Angular Momentum of Multipole Radiation	432
9.9	Angular Distribution of Multipole Radiation	437
9.10	Sources of Multipole Radiation: Multipole Moments	439
9.11	Multipole Radiation in Atoms and Nuclei	442
9.12	Multipole Radiation from a Linear, Center-Fed Antenna	444
	<i>References and Suggested Reading</i>	448
	<i>Problems</i>	449

Chapter 10 / Scattering and Diffraction

456

10.1	Scattering at Long Wavelengths	456
10.2	Perturbation Theory of Scattering, Rayleigh's Explanation of the Blue Sky, Scattering by Gases and Liquids, Attenuation in Optical Fibers	462
10.3	Spherical Wave Expansion of a Vector Plane Wave	471
10.4	Scattering of Electromagnetic Waves by a Sphere	473
10.5	Scalar Diffraction Theory	478
10.6	Vector Equivalents of the Kirchhoff Integral	482
10.7	Vectorial Diffraction Theory	485
10.8	Babinet's Principle of Complementary Screens	488
10.9	Diffraction by a Circular Aperture; Remarks on Small Apertures	490
10.10	Scattering in the Short-Wavelength Limit	495
10.11	Optical Theorem and Related Matters	500
	<i>References and Suggested Reading</i>	506
	<i>Problems</i>	507

Chapter 11 / Special Theory of Relativity

514

11.1	The Situation Before 1900, Einstein's Two Postulates	515
11.2	Some Recent Experiments	518
11.3	Lorentz Transformations and Basic Kinematic Results of Special Relativity	524
11.4	Addition of Velocities; 4-Velocity	530
11.5	Relativistic Momentum and Energy of a Particle	533
11.6	Mathematical Properties of the Space-Time of Special Relativity	539
11.7	Matrix Representation of Lorentz Transformations, Infinitesimal Generators	543
11.8	Thomas Precession	548
11.9	Invariance of Electric Charge; Covariance of Electrodynamics	553
11.10	Transformation of Electromagnetic Fields	558
11.11	Relativistic Equation of Motion for Spin in Uniform or Slowly Varying External Fields	561
11.12	Note on Notation and Units in Relativistic Kinematics	565
	<i>References and Suggested Reading</i>	566
	<i>Problems</i>	568