Classical Electrodynamics

Second Edition

JOHN DAVID JACKSON

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To the memory of my father,
Walter David Jackson

Preface

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 The old pseudo-Euclidean metric with $x_4 = ict$ has been replaced by $g^{\mu\nu}$ (with $g^{00} = +1$, $g^{ii} = -1$, $i = 1, 2, 3$).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) semiclassical 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!

Berkeley, California, 1974

J. D. Jackson

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 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 Chapters 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 multipole 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
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