

Problems in Classical Electromagnetism

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157 Exercises with Solutions

 Springer

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Preface

This book comprises 157 problems in classical electromagnetism, originating from the second-year course given by the authors to the undergraduate students of physics at the University of Pisa in the years from 2002 to 2017. Our course covers the basics of classical electromagnetism in a fairly complete way. In the first part, we present electrostatics and magnetostatics, electric currents, and magnetic induction, introducing the complete set of Maxwell's equations. The second part is devoted to the conservation properties of Maxwell's equations, the classical theory of radiation, the relativistic transformation of the fields, and the propagation of electromagnetic waves in matter or along transmission lines and waveguides. Typically, the total amount of lectures and exercise classes is about 90 and 45 hours, respectively. Most of the problems of this book were prepared for the intermediate and final examinations. In an examination test, a student is requested to solve two or three problems in 3 hours. The more complex problems are presented and discussed in detail during the classes.

The prerequisite for tackling these problems is having successfully passed the first year of undergraduate studies in physics, mathematics, or engineering, acquiring a good knowledge of elementary classical mechanics, linear algebra, differential calculus for functions of one variable. Obviously, classical electromagnetism requires differential calculus involving functions of more than one variable. This, in our undergraduate programme, is taught in parallel courses of the second year. Typically, however, the basic concepts needed to write down the Maxwell equations in differential form are introduced and discussed in our electromagnetism course, in the simplest possible way. Actually, while we do not require higher mathematical methods as a prerequisite, the electromagnetism course is probably the place where the students will encounter for the first time topics such as Fourier series and transform, at least in a heuristic way.

In our approach to teaching, we are convinced that checking the ability to solve a problem is the best way, or perhaps the only way, to verify the understanding of the theory. At the same time, the problems offer examples of the application of the theory to the real world. For this reason, we present each problem with a title that often highlights its connection to different areas of physics or technology,

so that the book is also a survey of historical discoveries and applications of classical electromagnetism. We tried in particular to pick examples from different contexts, such as, e.g., astrophysics or geophysics, and to include topics that, for some reason, seem not to be considered in several important textbooks, such as, e.g., radiation pressure or homopolar/unipolar motors and generators. We also included a few examples inspired by recent and modern research areas, including, e.g., optical metamaterials, plasmonics, superintense lasers. These latter topics show that nowadays, more than 150 years after Maxwell's equations, classical electromagnetism is still a vital area, which continuously needs to be understood and revisited in its deeper aspects. These certainly cannot be covered in detail in a second-year course, but a selection of examples (with the removal of unnecessary mathematical complexity) can serve as a useful introduction to them. In our problems, the students can have a first glance at “advanced” topics such as, e.g., the angular momentum of light, longitudinal waves and surface plasmons, the principles of laser cooling and of optomechanics, or the longstanding issue of radiation friction. At the same time, they can find the essential notions on, e.g., how an optical fiber works, where a plasma display gets its name from, or the principles of funny homemade electrical motors seen on YouTube.

The organization of our book is inspired by at least two sources, the book *Selected Problems in Theoretical Physics* (ETS Pisa, 1992, in Italian; World Scientific, 1994, in English) by our former teachers and colleagues A. Di Giacomo, G. Paffuti and P. Rossi, and the great archive of *Physics Examples and other Pedagogic Diversions* by Prof. K. McDonald (<http://puhep1.princeton.edu/%7Emcdonald/examples/>) which includes probably the widest source of advanced problems and examples in classical electromagnetism. Both these collections are aimed at graduate and postgraduate students, while our aim is to present a set of problems and examples with valuable physical contents, but accessible at the undergraduate level, although hopefully also a useful reference for the graduate student as well.

Because of our scientific background, our inspirations mostly come from the physics of condensed matter, materials and plasmas as well as from optics, atomic physics and laser–matter interactions. It can be argued that most of these subjects essentially require the knowledge of quantum mechanics. However, many phenomena and applications can be introduced within a classical framework, at least in a phenomenological way. In addition, since classical electromagnetism is the first field theory met by the students, the detailed study of its properties (with particular regard to conservation laws, symmetry relations and relativistic covariance) provides an important training for the study of wave mechanics and quantum field theories, that the students will encounter in their further years of physics study.

In our book (and in the preparation of tests and examinations as well), we tried to introduce as many original problems as possible, so that we believe that we have reached a substantial degree of novelty with respect to previous textbooks. Of course, the book also contains problems and examples which can be found in existing literature: this is unavoidable since many classical electromagnetism problems are, indeed, classics! In any case, the solutions constitute the most

important part of the book. We did our best to make the solutions as complete and detailed as possible, taking typical questions, doubts and possible mistakes by the students into account. When appropriate, alternative paths to the solutions are presented. To some extent, we tried not to bypass tricky concepts and ostensible ambiguities or “paradoxes” which, in classical electromagnetism, may appear more often than one would expect.

The sequence of Chapters 1–12 follows the typical order in which the contents are presented during the course, each chapter focusing on a well-defined topic. Chapter 13 contains a set of problems where concepts from different chapters are used, and may serve for a general review. To our knowledge, in some undergraduate programs the second-year physics may be “lighter” than at our department, i.e., mostly limited to the contents presented in the first six chapters of our book (i.e., up to Maxwell’s equations) plus some preliminary coverage of radiation (Chapter 10) and wave propagation (Chapter 11). Probably this would be the choice also for physics courses in the mathematics or engineering programs. In a physics program, most of the contents of our Chapters 7–12 might be possibly presented in a more advanced course at the third year, for which we believe our book can still be an appropriate tool.

Of course, this book of problems must be accompanied by a good textbook explaining the theory of the electromagnetic field in detail. In our course, in addition to lecture notes (unpublished so far), we mostly recommend the volume II of the celebrated *Feynman Lectures on Physics* and the volume 2 of the *Berkeley Physics Course* by E. M. Purcell. For some advanced topics, the famous *Classical Electrodynamics* by J. D. Jackson is also recommended, although most of this book is adequate for a higher course. The formulas and brief descriptions given at the beginning of the chapter are not meant at all to provide a complete survey of theoretical concepts, and should serve mostly as a quick reference for most important equations and to clarify the notation we use as well.

In the first Chapters 1–6, we use both the SI and Gaussian c.g.s. system of units. This choice was made because, while we are aware of the wide use of SI units, still we believe the Gaussian system to be the most appropriate for electromagnetism because of fundamental reasons, such as the appearance of a single fundamental constant (the speed of light c) or the same physical dimensions for the electric and magnetic fields, which seems very appropriate when one realizes that such fields are parts of the same object, the electromagnetic field. As a compromise we used both units in that part of the book which would serve for a “lighter” and more general course as defined above, and switched definitely (except for a few problems) to Gaussian units in the “advanced” part of the book, i.e., Chapters 7–13. This choice is similar to what made in the 3rd Edition of the above-mentioned book by Jackson.

Problem-solving can be one of the most difficult tasks for the young physicist, but also one of the most rewarding and entertaining ones. This is even truer for the older physicist who tries to *create* a new problem, and admittedly we learned a lot from this activity which we pursued for 15 years (some say that the only person who certainly learns something in a course is the teacher!). Over this long time, occasionally we shared this effort and amusement with colleagues including in

particular Francesco Ceccherini, Fulvio Cornolti, Vanni Ghimenti, and Pietro Menotti, whom we wish to warmly acknowledge. We also thank Giuseppe Bertin for a critical reading of the manuscript. Our final thanks go to the students who did their best to solve these problems, contributing to an essential extent to improve them.

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