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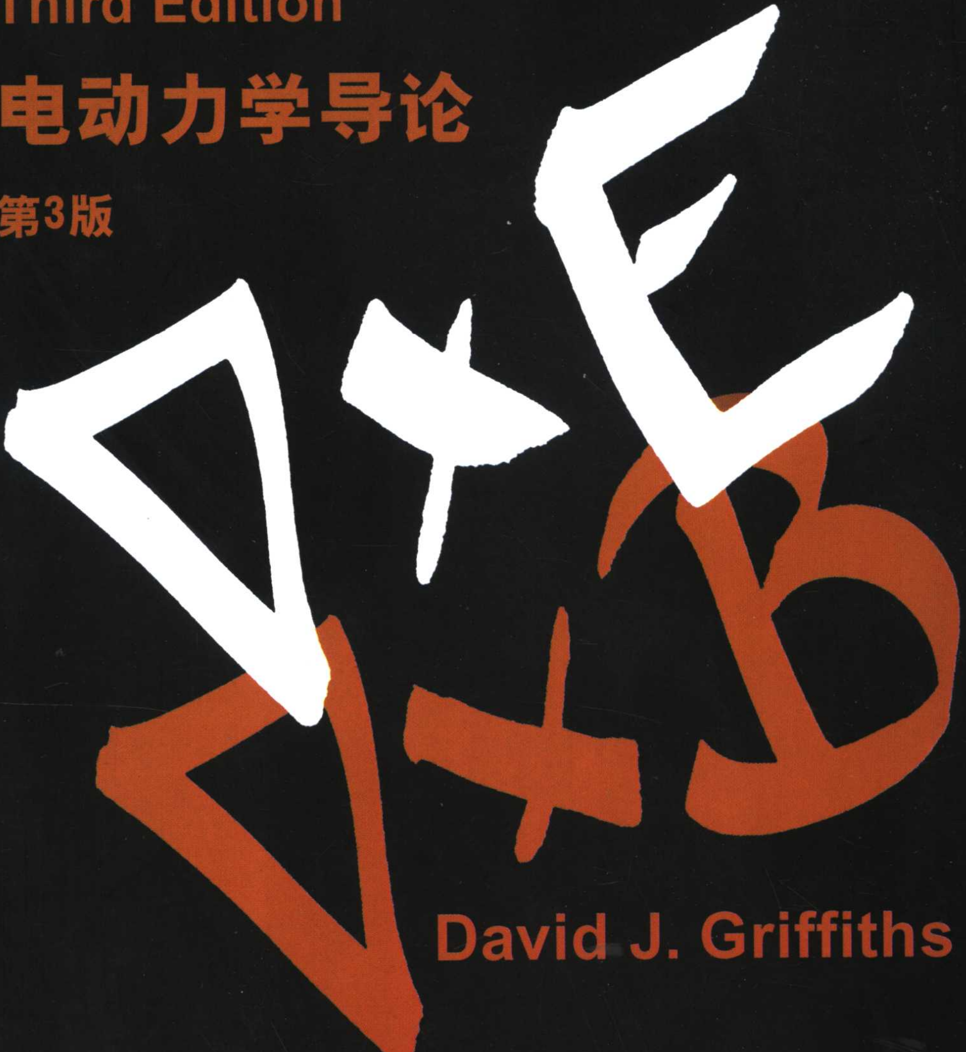
INTRODUCTION to ELECTRODYNAMICS

Third Edition

电动力学导论

第3版



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Introduction to Electrodynamics

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影印版前言

电动力学是大学本科物理系的一门支柱课程。它和理论力学、热力学和统计物理学以及量子力学一起通常称为“四大力学”，构成对学生进行基础物理学理论知识训练的核心，也是进一步学习更高等的基础课和各类专业课必不可少的准备知识。

在自然界已知的4种相互作用力（引力、电磁力、强相互作用力和弱相互作用力）中，电磁力是我们了解得最清楚的。它在我们日常的生活与生产活动以及各类技术的进步中起着无可置疑的支配作用。而电动力学正是介绍电磁规律的理论课程。因此，它不仅是物理系本科生的必修课，也是范围越来越广的理工科学生选修的课程。

从事电动力学教和学的师生，多年来一直有一个困惑，或者有一点遗憾：即除了国内一些专家撰写的教材以外，国外引进的适合本科使用的教材难得一见。大家熟悉的 Jackson 的名著《经典电动力学》（Classical Electrodynamics）是以研究生为对象的，其内容的深度与广度都不适宜本科生使用。而量子力学的情况则截然不同，随便就可以找到适合各种程度，风格各异的十几种外文教材。它们让师生们大开眼界，使他们不仅可以取长补短，改进教学，还可以在比较中鉴别，深化对于该课程的理解，进而发展自己具有独特风格的教材。

我们现在终于有机会向大家推荐由 Prentice Hall 出版社出版的一本面向本科生的优秀教材，它是由格里菲斯（David J. Griffiths）所著的《电动力学导论》（Introduction to Electrodynamics）。该书的第1版出版于1981年，由于其丰富的内容，新颖的叙述风格以及大量完整解出的例题而得到好评，被美国多所大学选为教材。这里影印的是1999年出版的第3版。该版改动了不少细节，把第1版第7章的两节扩充为新的两章，充实了对麦克斯韦方程物理意义的讨论。

本书是一部很有实际应用价值的教科书。清晰和完美是作者努力追求的目标。为了使其能自成完整的体系，本书的第1章用了很大篇幅讲述矢量分析，为电动力学的主要数学工具作了充分的准备。作者从一个比较低的起点开始正文的阐述，纳入了一些普通物理学中的电磁学知识，由浅入深地展开全文。全书的公式推导很详尽，这使本书易读易懂，适应更广泛

的读者对象。本书设计为两个学期教完，但对于基础比较好的学生，很多部分可以跳过去，一个学期完成全书的讲授是完全可能的。

本书选编了104个例题和530个习题，它们穿插安排在各个章节，成为本书重要的组成部分。它们对于理解课程内容，掌握解决实际问题的方法，扩大知识面至关重要。不少题目难度比较大，有的直接取自《美国物理学杂志》（American Journal of Physics）。因此有些读者曾经建议把习题解答附在书后，但遭到作者的强烈反对。他只同意对某些特别困难的题目提供答案或简单的提示。作为例外的是，对于集体购买超过一定数量，而且可以证明把本书选作教材的任课教师，可以向出版商索取带有全部解答的教学指南。此外还需要特别指出，本书的很多插图制作非常精美，这些清晰而直观的图像，对于理解物理结果有很大的帮助。

我们相信，本书的影印出版不仅会受到物理类理工科本科师生的欢迎，相关专业的研究生和科研人员也会从中受益。

中国科学院研究生院物理科学学院教授 丁亦兵
2005年12月

Preface

This is a textbook on electricity and magnetism, designed for an undergraduate course at the junior or senior level. It can be covered comfortably in two semesters, maybe even with room to spare for special topics (AC circuits, numerical methods, plasma physics, transmission lines, antenna theory, etc.) A one-semester course could reasonably stop after Chapter 7. Unlike quantum mechanics or thermal physics (for example), there is a fairly general consensus with respect to the teaching of electrodynamics; the subjects to be included, and even their order of presentation, are not particularly controversial, and textbooks differ mainly in style and tone. My approach is perhaps less formal than most; I think this makes difficult ideas more interesting and accessible.

For the third edition I have made a large number of small changes, in the interests of clarity and grace. I have also modified some notation to avoid inconsistencies or ambiguities. Thus the Cartesian unit vectors $\hat{\imath}$, $\hat{\jmath}$, and $\hat{k}$ have been replaced with $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$, so that all vectors are bold, and all unit vectors inherit the letter of the corresponding coordinate. (This also frees up $\mathbf{k}$ to be the propagation vector for electromagnetic waves.) It has always bothered me to use the same letter r for the spherical coordinate (distance from the origin) and the cylindrical coordinate (distance from the z axis). A common alternative for the latter is ρ, but that has more important business in electrodynamics, and after an exhaustive search I settled on the underemployed letter s; I hope this unorthodox usage will not be confusing.

Some readers have urged me to abandon the script letter $\boldsymbol{\mathscr{r}}$ (the vector from a source point $\mathbf{r}'$ to the field point $\mathbf{r}$) in favor of the more explicit $\mathbf{r} - \mathbf{r}'$. But this makes many equations distractingly cumbersome, especially when the unit vector $\hat{\boldsymbol{\mathscr{r}}}$ is involved. I know from my own teaching experience that unwary students are tempted to read $\boldsymbol{\mathscr{r}}$ as $\mathbf{r}$—it certainly makes the integrals easier! I have inserted a section in Chapter 1 explaining this notation, and I hope that will help. If you are a student, please take note: $\boldsymbol{\mathscr{r}} \equiv \mathbf{r} - \mathbf{r}'$, which is *not* the same as $\mathbf{r}$. If you're a teacher, please warn your students to pay close attention to the meaning of $\boldsymbol{\mathscr{r}}$. I think it's *good* notation, but it does have to be handled with care.

The main structural change is that I have removed the conservation laws and potentials from Chapter 7, creating two new short chapters (8 and 10). This should more smoothly accommodate one-semester courses, and it gives a tighter focus to Chapter 7.

I have added some problems and examples (and removed a few that were not effective). And I have included more references to the accessible literature (particularly the *American Journal of Physics*). I realize, of course, that most readers will not have the time or inclination to consult these resources, but I think it is worthwhile anyway, if only to emphasize that electrodynamics, notwithstanding its venerable age, is very much alive, and intriguing new discoveries are being made all the time. I hope that occasionally a problem will pique your curiosity, and you will be inspired to look up the reference—some of them are real gems.

As in the previous editions, I distinguish two kinds of problems. Some have a specific pedagogical purpose, and should be worked immediately after reading the section to which they pertain; these I have placed at the pertinent point within the chapter. (In a few cases the solution to a problem is used later in the text; these are indicated by a bullet (•) in the left margin.) Longer problems, or those of a more general nature, will be found at the end of each chapter. When I teach the subject I assign some of these, and work a few of them in class. Unusually challenging problems are flagged by an exclamation point (!) in the margin. Many readers have asked that the answers to problems be provided at the back of the book; unfortunately, just as many are strenuously opposed. I have compromised, supplying answers when this seems particularly appropriate. A complete solution manual is available (to instructors) from the publisher.

I have benefitted from the comments of many colleagues—I cannot list them all here. But I would like to thank the following people for suggestions that contributed specifically to the third edition: Burton Brody (Bard), Steven Grimes (Ohio), Mark Heald (Swarthmore), Jim McTavish (Liverpool), Matthew Moelter (Puget Sound), Paul Nachman (New Mexico State), Gigi Quartapelle (Milan), Carl A. Rotter (West Virginia), Daniel Schroeder (Weber State), Juri Silmberg (Ryerson Polytechnic), Walther N. Spjeldvik (Weber State), Larry Tankersley (Naval Academy), and Dudley Towne (Amherst). Practically everything I know about electrodynamics—certainly about teaching electrodynamics—I owe to Edward Purcell.

David J. Griffiths

Advertisement

What is electrodynamics, and how does it fit into the general scheme of physics?

Four Realms of Mechanics

In the diagram below I have sketched out the four great realms of mechanics:

Classical Mechanics (Newton)	**Quantum Mechanics** (Bohr, Heisenberg, Schrödinger, *et al.*)
Special Relativity (Einstein)	**Quantum Field Theory** (Dirac, Pauli, Feynman, Schwinger, *et al.*)

Newtonian mechanics was found to be inadequate in the early years of this century—it's all right in "everyday life," but for objects moving at high speeds (near the speed of light) it is incorrect, and must be replaced by special relativity (introduced by Einstein in 1905); for objects that are extremely small (near the size of atoms) it fails for different reasons, and is superseded by quantum mechanics (developed by Bohr, Schrödinger, Heisenberg, and many others, in the twenties, mostly). For objects that are both very fast *and* very small (as is common in modern particle physics), a mechanics that combines relativity and quantum principles is in order: this relativistic quantum mechanics is known as quantum field theory—it was worked out in the thirties and forties, but even today it cannot claim to be a completely satisfactory system. In this book, save for the last chapter, we shall work exclusively in the domain of classical mechanics, although electrodynamics extends with unique simplicity to the other three realms. (In fact, the theory is in most respects *automatically* consistent with special relativity, for which it was, historically, the main stimulus.)

Four Kinds of Forces

Mechanics tells us how a system will behave when subjected to a given *force*. There are just *four* basic forces known (presently) to physics: I list them in the order of decreasing strength:

1. Strong
2. Electromagnetic
3. Weak
4. Gravitational

The brevity of this list may surprise you. Where is friction? Where is the "normal" force that keeps you from falling through the floor? Where are the chemical forces that bind molecules together? Where is the force of impact between two colliding billiard balls? The answer is that *all* these forces are *electromagnetic*. Indeed, it is scarcely an exaggeration to say that we live in an electromagnetic world—for virtually every force we experience in everyday life, with the exception of gravity, is electromagnetic in origin.

The **strong forces**, which hold protons and neutrons together in the atomic nucleus, have extremely short range, so we do not "feel" them, in spite of the fact that they are a hundred times more powerful than electrical forces. The **weak forces**, which account for certain kinds of radioactive decay, are not only of short range; they are far weaker than electromagnetic ones to begin with. As for gravity, it is so pitifully feeble (compared to all of the others) that it is only by virtue of huge mass concentrations (like the earth and the sun) that we ever notice it at all. The electrical repulsion between two electrons is 10^{42} times as large as their gravitational attraction, and if atoms were held together by gravitational (instead of electrical) forces, a single hydrogen atom would be much larger than the known universe.

Not only are electromagnetic forces overwhelmingly the dominant ones in everyday life, they are also, at present, the *only* ones that are completely understood. There is, of course, a classical theory of gravity (Newton's law of universal gravitation) and a relativistic one (Einstein's general relativity), but no entirely satisfactory quantum mechanical theory of gravity has been constructed (though many people are working on it). At the present time there is a very successful (if cumbersome) theory for the weak interactions, and a strikingly attractive candidate (called **chromodynamics**) for the strong interactions. All these theories draw their inspiration from electrodynamics; none can claim conclusive experimental verification at this stage. So electrodynamics, a beautifully complete and successful theory, has become a kind of paradigm for physicists: an ideal model that other theories strive to emulate.

The laws of classical electrodynamics were discovered in bits and pieces by Franklin, Coulomb, Ampère, Faraday, and others, but the person who completed the job, and packaged it all in the compact and consistent form it has today, was James Clerk Maxwell. The theory is now a little over a hundred years old.

The Unification of Physical Theories

In the beginning, **electricity** and **magnetism** were entirely separate subjects. The one dealt with glass rods and cat's fur, pith balls, batteries, currents, electrolysis, and lightning; the other with bar magnets, iron filings, compass needles, and the North Pole. But in 1820 Oersted noticed that an *electric* current could deflect a *magnetic* compass needle. Soon afterward, Ampère correctly postulated that *all* magnetic phenomena are due to electric charges in motion. Then, in 1831, Faraday discovered that a moving *magnet* generates an *electric* current. By the time Maxwell and Lorentz put the finishing touches on the theory, electricity and magnetism were inextricably intertwined. They could no longer be regarded as separate subjects, but rather as two *aspects* of a *single* subject: **electromagnetism**.

Faraday had speculated that light, too, is electrical in nature. Maxwell's theory provided spectacular justification for this hypothesis, and soon **optics**—the study of lenses, mirrors, prisms, interference, and diffraction—was incorporated into electromagnetism. Hertz, who presented the decisive experimental confirmation for Maxwell's theory in 1888, put it this way: "The connection between light and electricity is now established ... In every flame, in every luminous particle, we see an electrical process ... Thus, the domain of electricity extends over the whole of nature. It even affects ourselves intimately: we perceive that we possess ... an electrical organ—the eye." By 1900, then, three great branches of physics, electricity, magnetism, and optics, had merged into a single unified theory. (And it was soon apparent that visible light represents only a tiny "window" in the vast spectrum of electromagnetic radiation, from radio through microwaves, infrared and ultraviolet, to x-rays and gamma rays.)

Einstein dreamed of a further unification, which would combine gravity and electrodynamics, in much the same way as electricity and magnetism had been combined a century earlier. His **unified field theory** was not particularly successful, but in recent years the same impulse has spawned a hierarchy of increasingly ambitious (and speculative) unification schemes, beginning in the 1960s with the **electroweak** theory of Glashow, Weinberg, and Salam (which joins the weak and electromagnetic forces), and culminating in the 1980s with the **superstring** theory (which, according to its proponents, incorporates all four forces in a single "theory of everything"). At each step in this hierarchy the mathematical difficulties mount, and the gap between inspired conjecture and experimental test widens; nevertheless, it is clear that the unification of forces initiated by electrodynamics has become a major theme in the progress of physics.

The Field Formulation of Electrodynamics

The fundamental problem a theory of electromagnetism hopes to solve is this: I hold up a bunch of electric charges *here* (and maybe shake them around)—what happens to some other charge, over *there?* The classical solution takes the form of a **field theory**: We say that the space around an electric charge is permeated by electric and magnetic **fields** (the electromagnetic "odor," as it were, of the charge). A second charge, in the presence of these fields, experiences a force; the fields, then, transmit the influence from one charge to the other—they mediate the interaction.

When a charge undergoes *acceleration*, a portion of the field "detaches" itself, in a sense, and travels off at the speed of light, carrying with it energy, momentum, and angular momentum. We call this **electromagnetic radiation**. Its existence invites (if not *compels*) us to regard the fields as independent dynamical entities in their own right, every bit as "real" as atoms or baseballs. Our interest accordingly shifts from the study of forces between charges to the theory of the fields themselves. But it takes a charge to *produce* an electromagnetic field, and it takes another charge to *detect* one, so we had best begin by reviewing the essential properties of electric charge.

Electric Charge

1. *Charge comes in two varieties,* which we call "plus" and "minus," because their effects tend to *cancel* (if you have $+q$ and $-q$ at the same point, electrically it is the same as having no charge there at all). This may seem too obvious to warrant comment, but I encourage you to contemplate other possibilities: what if there were 8 or 10 different species of charge? (In chromodynamics there are, in fact, *three* quantities analogous to electric charge, each of which may be positive or negative.) Or what if the two kinds did not tend to cancel? The extraordinary fact is that plus and minus charges occur in *exactly* equal amounts, to fantastic precision, in bulk matter, so that their effects are almost completely neutralized. Were it not for this, we would be subjected to enormous forces: a potato would explode violently if the cancellation were imperfect by as little as one part in 10^{10}.

2. *Charge is conserved:* it cannot be created or destroyed—what there is now has always been. (A plus charge can "annihilate" an equal minus charge, but a plus charge cannot simply disappear by itself—*something* must account for that electric charge.) So the total charge of the universe is fixed for all time. This is called **global** conservation of charge. Actually, I can say something much stronger: Global conservation would allow for a charge to disappear in New York and instantly reappear in San Francisco (that wouldn't affect the *total*), and yet we know this doesn't happen. If the charge *was* in New York and it *went* to San Francisco, then it must have passed along some continuous path from one to the other. This is called **local** conservation of charge. Later on we'll see how to formulate a precise mathematical law expressing local conservation of charge—it's called the **continuity equation**.

3. *Charge is quantized.* Although nothing in classical electrodynamics requires that it be so, the *fact* is that electric charge comes only in discrete lumps—integer multiples of the basic unit of charge. If we call the charge on the proton $+e$, then the electron carries charge $-e$, the neutron charge zero, the pi mesons $+e$, 0, and $-e$, the carbon nucleus $+6e$, and so on (never $7.392e$, or even $1/2e$).[1] This fundamental unit of charge is extremely small, so for practical purposes it is usually appropriate to ignore quantization altogether. Water, too, "really" consists of discrete lumps (molecules); yet, if we are dealing with reasonably large large quantities of it we can treat it as a continuous fluid. This is in fact much closer to Maxwell's own view; he knew nothing of electrons and protons—he must have pictured

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[1] Actually, protons and neutrons are composed of three **quarks**, which carry fractional charges ($\pm\frac{2}{3}e$ and $\pm\frac{1}{3}e$). However, *free* quarks do not appear to exist in nature, and in any event this does not alter the fact that charge is quantized; it merely reduces the size of the basic unit.

charge as a kind of "jelly" that could be divided up into portions of any size and smeared out at will.

These, then, are the basic properties of charge. Before we discuss the forces *between* charges, some mathematical tools are necessary; their introduction will occupy us in Chapter 1.

Units

The subject of electrodynamics is plagued by competing systems of units, which sometimes render it difficult for physicists to communicate with one another. The problem is far worse than in mechanics, where Neanderthals still speak of pounds and feet; for in mechanics at least all equations *look* the same, regardless of the units used to measure quantities. Newton's second law remains $\mathbf{F} = m\mathbf{a}$, whether it is feet-pounds-seconds, kilograms-meters-seconds, or whatever. But this is not so in electromagnetism, where Coulomb's law may appear variously as

$$\frac{q_1 q_2}{\mathscr{r}^2}\hat{\boldsymbol{\mathscr{r}}} \;\text{(Gaussian)}, \quad \text{or} \quad \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{\mathscr{r}^2}\hat{\boldsymbol{\mathscr{r}}} \;\text{(SI)}, \quad \text{or} \quad \frac{1}{4\pi}\frac{q_1 q_2}{\mathscr{r}^2}\hat{\boldsymbol{\mathscr{r}}} \;\text{(HL)}.$$

Of the systems in common use, the two most popular are **Gaussian** (cgs) and **SI** (mks). Elementary particle theorists favor yet a third system: **Heaviside-Lorentz**. Although Gaussian units offer distinct theoretical advantages, most undergraduate instructors seem to prefer SI, I suppose because they incorporate the familiar household units (volts, amperes, and watts). In this book, therefore, I have used SI units. Appendix C provides a "dictionary" for converting the main results into Gaussian units.

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