Graduate Texts in Physics

Carl S. Helrich

The Classical Theory of Fields

Electromagnetism

经典场论

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Electromagnetism

With 132 Figures

Springer

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Preface

The study of classical electromagnetic fields is an adventure. The theory is complete mathematically and we are able to present it as an example of classical Newtonian experimental and mathematical philosophy. There is a set of foundational experiments on which most of the theory is constructed. And then there is the bold theoretical proposal of a field–field interaction from James Clerk Maxwell, the validity of which was established in Heinrich Hertz' laboratory.

It is my intention here to present the theory of classical fields as a mathematical structure based solidly on laboratory experiments. I try to introduce the reader – the student – to the beauty of classical field theory as a gem of theoretical physics.

To keep the discussion fluid I placed the history in a beginning chapter and some of the mathematical proofs in the Appendices. Helmholtz' Theorem determines the form that will be taken by the field equations and the way in which we must understand each experiment. To obtain Maxwell's field equations is the goal. If the reader also learns to work through exercises that is good. But that is not the goal. The problems the reader will encounter as a practioner will require thinking that must be based on a deep understanding of classical field theory.

And so I have tried to obtain Maxwell's Equations as soon as possible. I have not been completely successful because of my concerns about the reader's mathematical development. I felt compelled to include a rather extensive chapter on mathematical background for readers unfamiliar with some of the language. I have also included chapters on Green's Functions and Laplace's Equation between the static form of Maxwell's Equations and a discussion of Faraday's Experiment. These may be avoided by the reader already fluent in the mathematics.

The chapter on Einstein's relativity is an integral necessity to the text. This chapter is historically accurate and fairly complete for the level of the text. My treatment is based on original papers by Einstein, Hendrik A. Lorentz, and Hermann Minkowski, on the excellent historical analysis of Abraham Pais, and on some more modern treatments such as Wolfgang Pauli's and Wolfgang Rindler's. My goal is to demonstrate the covariance of Maxwell's Equations and to present the transformation theory, while not losing sight of the "step" that had been introduced. I do not suggest ignoring this chapter. It is good for the physicist's or engineer's soul to know about this step. But it is not absolutely required for much of the use to which a practitioner will put field theory.

I have tried to be honest with the reader about our microscopic picture of matter. I avoid quantum mechanical descriptions, but not the fact that these lie behind our treatment of matter.

Our models of plasmas provide a good testing ground for electrodynamic theory that does not require quantum mechanics. I have used this at points in the text. This has been my guide in the chapter on particle motion and in my final chapter on waves in a dispersive medium.

My discussions of particle motion are based on Hamiltonian mechanics, which I outline. This results in a symmetry, as well as simplicity in the equations of motion. My treatment of magnetic mirrors relies on numerical solutions, which are simplified by the canonical equations. And I have based my discussion of coherent particle motion verbally on what is known of the dynamics of plasmas.

I have not intended this treatment to be exhaustive. The topics I have chosen reflect my interests as well as what I felt my own education lacked. I will, probably, readily agree with any criticism claiming that I have missed an indispensable topic. I do, however, believe that after finishing this text the reader should be able to encounter that topic with confidence.

I am grateful to generations of students who have helped in the development of my course in classical field theory. Their patience and enthusiasm has been an inspiration.

I am also grateful to my teachers and the directors of programs in which I have been involved. Among these I particularly want to acknowledge Leslie Foldy, David Mintzer, Marvin Lewis, and Günter Ecker. From each of these people I have learned to be thorough, unrelenting, and even confident. The first three of these people were inspiring teachers, Lewis was my doctoral mentor, and Ecker was my director in Jülich.

I have discussed modern plasma theory, of which I am no longer a part, extensively with my friend Wei-li Lee of the Princeton Plasma Physics Laboratory. Lee contributed directly to my discussions of gyrokinetic theory and its application to magnetically confined fusion plasmas.

I am grateful for the patience and understanding of my wife, Betty Jane, who has endured more than I could have expected as I wrote this, and who remained a constant source of encouragement.

I am thankful for the encouragement and positive discussions from Dr. Thorsten Schneider and Ms. Birgit Münch of Springer-Verlag and the very careful work of Ms. Deepthi Mohan of SPi Technologies India.

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Goshen, Indiana *Carl Helrich*

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Chapter 1
Origins and Concepts

Gravity must be caused by an Agent acting constantly according to certain Laws; but whether this agent be material or immaterial, I have left to the Consideration of my Readers.

Isaac Newton

The field concept is the product of a highly original mind, a mind which never got stuck on formulas.

Albert Einstein

1.1 Introduction

Classical field theory possesses a striking beauty in part because it comes to us as a complete theory in which we can tie almost each law and concept directly to a single experiment. Except for the qualifying "almost" we can present the subject as based on hard laboratory data and a very limited number of guiding ideas. But there is too much human thought that lies behind the word "almost" for us to drop it in our pursuit of understanding.

The history of science is a history of human thought. Because there is no simple understanding of the origin of ideas there can be no simple understanding of the development of any branch of science. And our understanding of a branch of science is linked to how well we comprehend the origin of the ideas on which it rests.

Classical field theory began as a logical extension of what we already knew from Isaac Newton's experimental and mathematical philosophy [79, pp. 214–215] and the mechanics that resulted. Newton, however, knew that his law of universal gravitation begged an explanation that lay beyond the experimental data.

Michael Faraday (1791–1867), whom we acknowledge as the greatest among experimentalists, imagined that lines of force permeated space and were responsible for electric and magnetic phenomena. This was heresy. But it was believed by William Thomson (1824–1907) and James Clerk Maxwell (1831–1879). Maxwell's

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mathematical development of Faraday's ideas, and the conviction that light waves must emerge from the theory, will bring us to a point where theory presses experiment.

Heinrich Hertz (1857–1894), in the laboratory in Karlsruhe, carried out the experiments that identified propagating electromagnetic waves. But this alone did not reveal the full truth, as Hertz knew.

We must also encounter the crisis in scientific thought that marked the beginning of the twentieth century. The answers presented by Albert Einstein in 1905 required a revision of the bedrock of Newtonian thought: the concept of time and consequently of space.

Classical field theory will then bring us new ideas that we could not have anticipated. In this chapter we will trace the twisted historical path with the intention of seeing the origin of ideas and the consequences. To fully understand classical field theory as a product of human thought we must encounter these origins and consequences.

We will have many occasions to reference this chapter.

1.2 Magnetism

In 1849 Thomson first used the term *field of force*, or simply *field*, in reference to magnetic effects [18, p. 146]. He was providing new words for Faraday's idea of lines of force. He was also, at least in part, giving words to the same phenomenon that had such an impression on Einstein when he was four years of age. Einstein had marveled at the fact that a compass needle responded to a magnet although there was nothing between the needle and the magnet [65, p. 3].

Faraday was a mature scientist in 1849. His lines of force gave expression to a conviction that we should not simply accept a description in the language of action at a distance. In Faraday's mind the space surrounding a magnet or an electrical charge was not empty. It was penetrated by magnetic or electric lines of force. These lines of force are responsible for what we experience when we bring the like poles of two permanent magnets close to one another. But Faraday also believed that such lines of force were present around any mass and were the source of the gravitational force [18, p. 147].

In a lecture he gave at the Royal Institution in 1834, three years after his discovery that electric currents result from variations in magnetism, Faraday claimed that, "We cannot say that any one is the cause of the others, but only that they are connected and due to a common cause" [18, p. 145].

In 1845 Faraday found the effect of magnetism on the polarization of light. In the paper reporting this effect he stated his conviction that the various forms of the forces of matter have one common origin. This was a great scientist and a very careful experimentalist speaking out of his experience. Faraday saw a universe permeated by fields where the nineteenth century theoreticians saw Newtonian particles and action at a distance.