Preface

This is the third in a series of four volumes, all written at an elementary calculus level. The complete course covers the most important areas of classical physics, such as mechanics, thermodynamics, statistical mechanics, electromagnetism, waves and optics. The volumes are the result of a translation, an in-depth revision, and an update of the Italian version published by Decibel–Zanichelli. This third volume deals with classical electromagnetism.

The vast majority of physics phenomena naturally taking place around us originate in electromagnetic forces. The largest portion of the technology that holds sway over so much of our lives and our civilization is the result of our knowledge and control of electromagnetic forces.

The forces that keep atoms together internally, binding electrons to nuclei, and externally, binding those atoms within molecules, are electromagnetic. As a consequence, the energies developed in all chemical reactions are electromagnetic, including the biochemical ones, which are the basis of life itself. Contact forces, such as friction, between solid surfaces are electromagnetic, and so is the drag force acting on a body moving in a fluid. Elastic forces, cohesion forces, and the force that results from the earth's magnetism are all electromagnetic. Light itself is an electromagnetic wave, whose wavelength is in the range to which our eyes are sensitive. The radio waves we use in telecommunications, radio, television, and cellular phones are electromagnetic as well, utilizing much greater wavelengths. As a matter of fact, all the phenomena on scales larger than those of the atomic and molecular have a gravitational or electromagnetic origin.

Modern technology is more than 99 % reliant on electromagnetism. In hydroelectric power stations, for example, big turbines are moved by water falling on them through large pipes under pressure. The turbines move electromagnetic generators, made of massive copper coils rotating between the poles of an electromagnet. The generators produce an electromotive force that is then distributed through a network of thousands of copper wires across distances of hundreds of kilometers to factories, offices, and houses. Here, the electric power is used by electric motors to produce all types of objects, to control chemical processes, or simply to light our rooms or wash our dishes. All of these are electromagnetic processes. Cellular phones emit and receive electromagnetic waves, which are produced or detected and amplified by electronic circuits. Our computers store, process, and transmit information using electronic circuits of ever-increasing complexity and miniaturization.

However, the electromagnetic nature of natural phenomena does not appear at first sight and remained substantially unknown until roughly two centuries ago. Lighting is the phenomenon with the most evident (to us) electric nature, but it was not the genesis of the study of electric and magnetic phenomena. On the contrary, the first observations were in regard to the curious properties of amber, which, when rubbed, attracted small pieces of papyrus, and of magnetite, a stone capable of attracting pieces of iron. These phenomena were reported by the Greek philosopher Thales from Miletus in the sixth century BC. Twenty-two centuries had to pass before the first systematic observations and the first attempts at interpretation of electric and magnetic phenomena would occur, with William Gilbert's publication of his work in the book *De magnete* in 1600. Still, almost two more centuries would go by before Charles Augustin de Coulomb would make the fundamental measurement of the electric force between two charges and its dependence on their distance in 1785, finally paving the way for electric and magnetic research.

The basic reason for this late scientific birth of electromagnetism can be traced to the fact that, even if the electric force is billions of billions of billions of billions stronger than the gravitational force, it can be attractive or repulsive, depending on the sign of the charges, and because matter is made of positive and negative charges so exactly equal and opposite and so intimately mixed together that they perfectly balance one another. Nobody knows, even today, the reason for this perfect equality. Phenomena in different sectors of physics, mechanics or acoustics, for example, have always been known to the common man, and later scientists have gradually discovered the underlying laws. Contrastingly, the entire electromagnetic world is a discovery of science.

The life spans of the principal contributors to electromagnetism are shown in Fig. 1.

The next fundamental step forward after Coulomb was credited to Alessandro Volta, who published his discovery of the pile in 1800. The production of voltages and electric currents became available for further experiments and the pace of progress grew very rapidly, leading to a complete understanding of electromagnetism in less than a century. Volta's pile made possible the experiment with which Hans Christian Ørsted, in 1820, first discovered the magnetic effects of electric currents, connecting electricity and magnetism for the first time. Between 1820 and 1826, André Marie Ampère completely clarified the relation between the magnetic field and electric currents with a series of beautiful experiments. In 1831, Michael Faraday discovered electromagnetic induction, the phenomenon in which magnetic fields variable with time produce electric fields. Finally, in 1865, James Clerk Maxwell wrote the differential equations that contain the complete theory of electromagnetism. The equations not only foresaw a new phenomenon, electromagnetic waves, but also that light itself is such a wave. The theoretical prediction

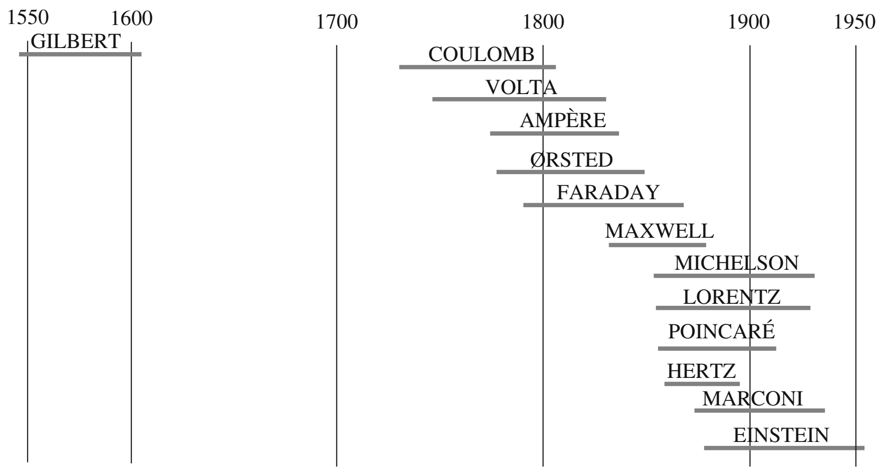

Fig. 1 Life spans of the greater contributors to electromagnetism

of the electromagnetic waves, specifically those that we call radio waves, was experimentally confirmed by Henrich Rudolf Hertz with a series of experiments, also quite beautiful, between 1886 and 1889. Twelve years later, in 1901, Guglielmo Marconi succeeded in sending the first radio transmission across the Atlantic Ocean. The message, consisting simply of the Morse code signal for the letter "s", traveled more than 2000 miles from Cornwall in England to Newfoundland in Canada.

As opposed to Galilei–Newton mechanics, the electromagnetic theory also appeared to hold in its original formulation of Maxwell at the highest velocities up to the speed of light. In other words, the electromagnetic theory was born being already relativistically correct. Better still, it was that very progress in the in-depth experimental study of electromagnetic phenomena, in particular, with the outstanding experiment of Albert Abraham Michelson (with Morley) in 1887, and the revolutionary theoretical analysis between 1895 and 1905 by, mainly, Hendrik Antoon Lorentz, Henri Poincaré and Albert Einstein, that led to special relativity.

Classical electromagnetism is a magnificent scientific construction that quantitatively describes a huge number of phenomena and is the basis of modern technology. However, it does not work in the interpretation of electromagnetic interaction at atomic or smaller scales. The experimental and theoretical progress over the past century led to the development of quantum electrodynamics, which contains the classical electrodynamics as an approximation valid on large enough scales and fully explains the phenomena down to the smallest scales explored experimentally thus far.

The scope of these lectures is the description, at an introductory level, of classical electromagnetism. The reader is assumed to be acquainted with differential calculus, including the simplest partial differential equations, the gradient, divergence and curl operators and their basic theorems.

Physics is an experimental science, meaning that it is based on the experimental method, which was developed by Galileo Galilei in the seventeenth century. The process of understanding physical phenomena is not immediate, but rather, it advances by trial and error, in a series of experiments, which might lead, with a bit of fortune and a lot of thinking, to the discovery of the governing laws. Induction of the process of physical laws goes back from the observed effects to their causes, and, as such, cannot be purely logical. Once a physical law is found, it is necessary to consider all its possible consequences. This is now a deductive process, which is logical and similar to that of mathematics. Each of the consequences, the predictions, of the law must then be experimentally verified. If only one prediction is found to be false by the experiment, even if thousands of them had been found true, it is enough to prove that the law is false. This implies that we can never be completely sure that a law is true; indeed, the number of its possible predictions is limitless, and at any historical moment, not all of them have been controlled. However, this is the price we must pay in choosing the experimental method, which has allowed humankind to advance much further in the last four centuries than in all the preceding millennia.

The path of science is complex, laborious, and highly nonlinear. In its development, errors have been made and hypotheses have been advanced that turned out to be false, but ultimately, laws were discovered. The knowledge of at least a few of the most important aspects of this process is indispensable for developing the mental capabilities necessary for anybody who wishes to contribute to the progress of natural sciences, whether they pursue applications or teach them. It is for this reason that we shall read and discuss the descriptions some of these authors have put forth of their fundamental experiments.

Each chapter of the book starts with a brief introduction on a scope that will give the reader a preliminary idea of the arguments he/she will find. There is no need to fully understand these introductions at the first reading, as all the arguments are fully developed in the subsequent pages.

At the end of each chapter, the reader will find a summary and a number of queries with which to check his/her level of understanding of the chapter's arguments. The difficulty of the queries is variable; some of them are very simple, some more complex, a few are true numerical exercises. However, the book does not contain any sequence of full exercises, considering the existence of very good textbooks dedicated specifically to that.

The first four chapters deal with electrostatics, namely electric phenomena under time-independent conditions. Chapter 1 is on electrostatics in a vacuum. The concept of the electric charge is introduced and the basic properties of this fundamental physical quantity are discussed. We then discuss the force between charges at rest, introduce the concept of the electric field and discuss its properties. The materials can be schematically classified, from the electric point of view, into two main classes, the conductors and the insulators, which are also called dielectrics. We deal with the former in Chap. 2, and latter in Chap. 4. Chapter 3 is dedicated to the energy of the electrostatic systems in a vacuum and with conductors. Chapter 5 treats the steady electric currents. Chapter 6 is on magnetostatics, namely magnetic phenomena under time-independent conditions, in a vacuum. In Chap. 7, we start our study in dynamic, namely time-dependent, situations with the important phenomena of electromagnetic induction, which link electricity and magnetism. Chapter 8 is dedicated to the study of the energy of the magnetostatic systems in a vacuum. In Chap. 9, we study magnetic phenomena in the presence of matter, in particular, diamagnetism, paramagnetism, and ferromagnetism. Finally, in Chap. 10, we reach the full description of the Maxwell equations, both in a vacuum and in matter, discover the new phenomena they foresee and study the Lorentz invariance of the equations.

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