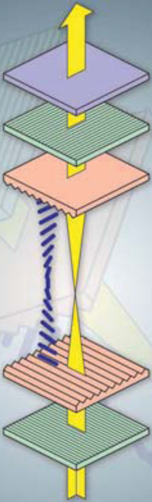
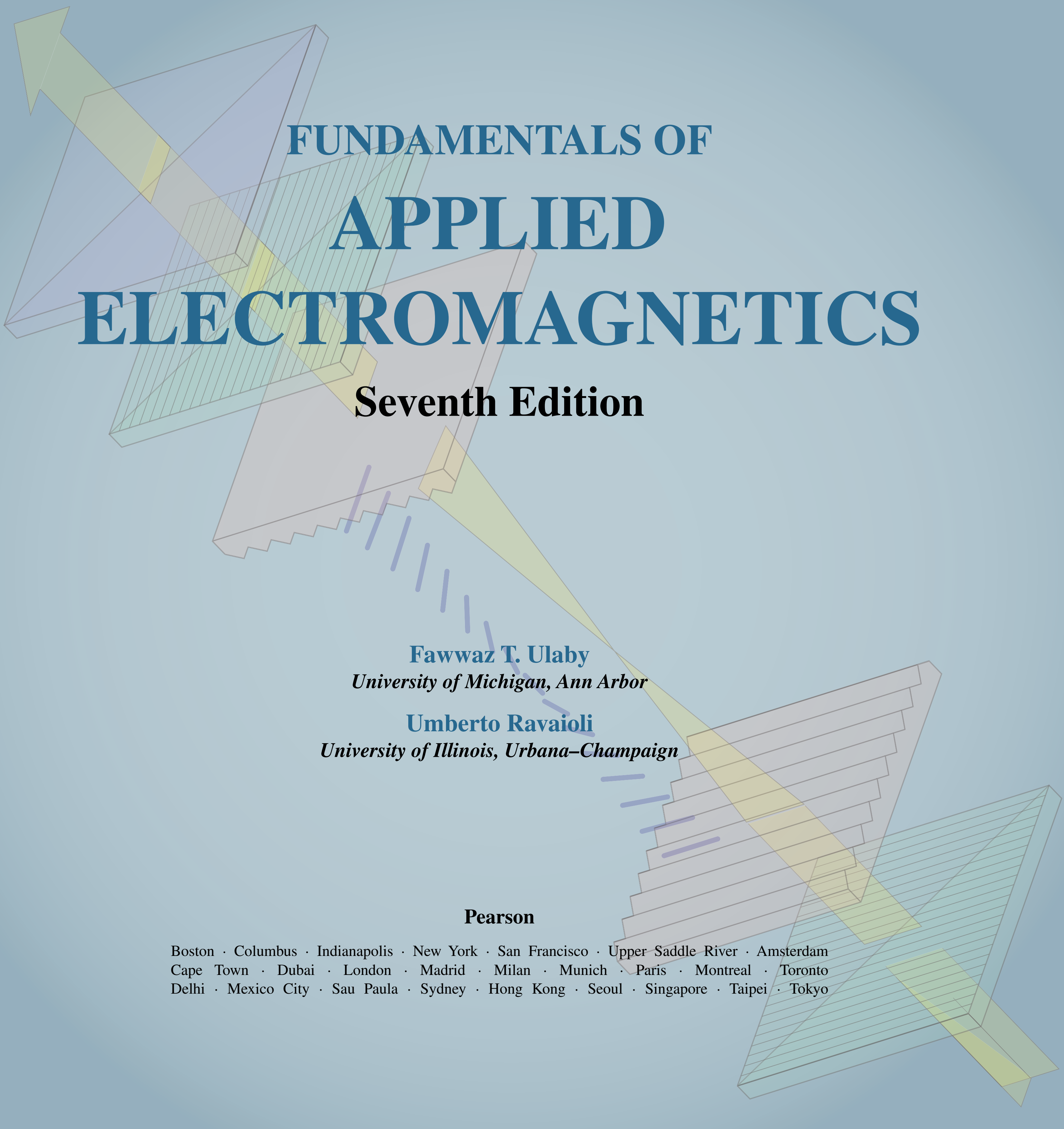
Fawwaz T. Ulaby | Umberto Ravaioli



FUNDAMENTALS OF APPLIED ELECTROMAGNETICS

Seventh Edition



FUNDAMENTALS OF
APPLIED ELECTROMAGNETICS

Seventh Edition

Fawwaz T. Ulaby
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We dedicate this book to
Jean and Ann Lucia.

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Preface to Seventh Edition

Building on the core content and style of its predecessor, this seventh edition (7/e) of *Applied Electromagnetics* introduces new features designed to help students develop a deeper understanding of electromagnetic concepts and applications. Prominent among them is a set of 52 web-based simulation modules that allow the user to interactively analyze and design transmission line circuits; generate spatial patterns of the electric and magnetic fields induced by charges and currents; visualize in 2-D and 3-D space how the gradient, divergence, and curl operate on spatial functions; observe the temporal and spatial waveforms of plane waves propagating in lossless and lossy media; calculate and display field distributions inside a rectangular waveguide; and generate radiation patterns for linear antennas and parabolic dishes. These are valuable learning tools; we encourage students to use them and urge instructors to incorporate them into their lecture materials and homework assignments.

Additionally, by enhancing the book's graphs and illustrations, and by expanding the scope of topics of the Technology Briefs, additional bridges between electromagnetic fundamentals and their countless engineering and scientific applications are established. In summary:

NEW TO THIS EDITION

- A set of 10 additional interactive simulation modules, bringing the total to 52
- Updated Technology Briefs
- Enhanced figures and images
- New/updated end-of-chapter problems
- The interactive modules and Technology Briefs can be found at the Student Website on http://www.pearsonhighered.com/ulaby.

ACKNOWLEDGMENTS

As authors, we were blessed to have worked on this book with the best team of professionals: Richard Carnes, Leland Pierce, Janice Richards, Rose Kernan, and Paul Mailhot. We are exceedingly grateful for their superb support and unwavering dedication to the project.

We enjoyed working on this book. We hope you enjoy learning from it.

Fawwaz T. Ulaby
Umberto Ravaioli

CONTENT

The book begins by building a bridge between what should be familiar to a third-year electrical engineering student and the electromagnetics (EM) material covered in the book. Prior to enrolling in an EM course, a typical student will have taken one or more courses in circuits. He or she should be familiar with circuit analysis, Ohm's law, Kirchhoff's current and voltage laws, and related topics. Transmission lines constitute a *natural* bridge between electric circuits and electromagnetics. Without having to deal with vectors or fields, the student uses already familiar concepts to learn about wave motion, the reflection and transmission of power, phasors, impedance matching, and many of the properties of wave propagation in a guided structure. All of these newly learned concepts will prove invaluable later (in Chapters 7 through 9) and will facilitate the learning of how plane waves propagate in free space and in material media. Transmission lines are covered in Chapter 2, which is preceded in Chapter 1 with reviews of complex numbers and phasor analysis.

The next part of the book, contained in Chapters 3 through 5, covers vector analysis, electrostatics, and magnetostatics. The electrostatics chapter begins with Maxwell's equations for the time-varying case, which are then specialized to electrostatics and magnetostatics, thereby providing the student with an overall framework for what is to come and showing him or her why electrostatics and magnetostatics are special cases of the more general time-varying case.

Chapter 6 deals with time-varying fields and sets the stage for the material in Chapters 7 through 9. Chapter 7 covers plane-wave propagation in dielectric and conducting media, and Chapter 8 covers reflection and transmission at discontinuous boundaries and introduces the student to fiber optics, waveguides and resonators.

In Chapter 9, the student is introduced to the principles of radiation by currents flowing in wires, such as dipoles, as well as

Suggested Syllabi

		Two-semester Syllabus 6 credits (42 contact hours per semester)		**One-semester Syllabus** 4 credits (56 contact hours)	
	Chapter	Sections	Hours	Sections	Hours
1	Introduction: Waves and Phasors	All	4	All	4
2	Transmission Lines	All	12	2-1 to 2-8 and 2-11	8
3	Vector Analysis	All	8	All	8
4	Electrostatics	All	8	4-1 to 4-10	6
5	Magnetostatics	All	7	5-1 to 5-5 and 5-7 to 5-8	5
	Exams		3		2
		Total for first semester	42		
6	Maxwell's Equations for Time-Varying Fields	All	6	6-1 to 6-3, and 6-6	3
7	Plane-wave Propagation	All	7	7-1 to 7-4, and 7-6	6
8	Wave Reflection and Transmission	All	9	8-1 to 8-3, and 8-6	7
9	Radiation and Antennas	All	10	9-1 to 9-6	6
10	Satellite Communication Systems and Radar Sensors	All	5	None	—
	Exams		3		1
		Total for second semester	40	Total	56
	Extra Hours		2		0

to radiation by apertures, such as a horn antenna or an opening in an opaque screen illuminated by a light source.

To give the student a taste of the wide-ranging applications of electromagnetics in today's technological society, Chapter 10 concludes the book with overview presentations of two system examples: satellite communication systems and radar sensors.

The material in this book was written for a two-semester sequence of six credits, but it is possible to trim it down to generate a syllabus for a one-semester four-credit course. The accompanying table provides syllabi for each of these two options.

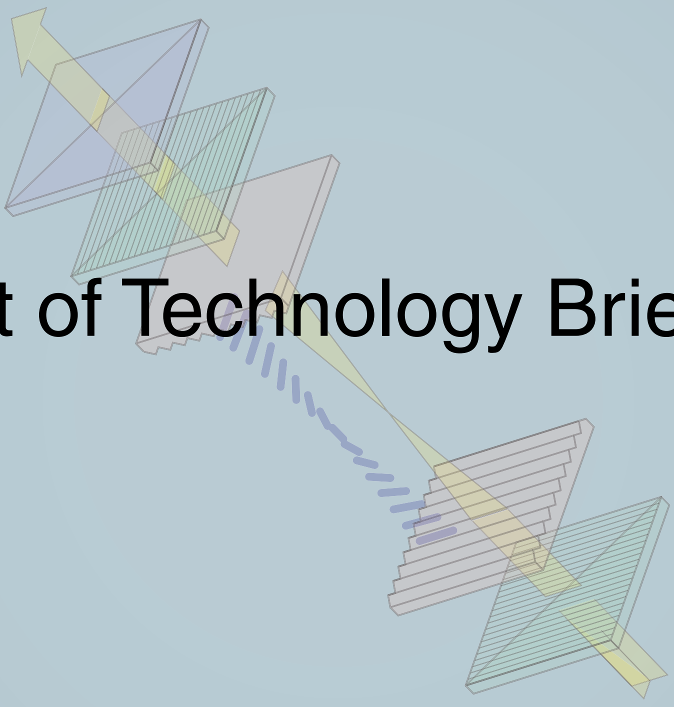
MESSAGE TO THE STUDENT

The web-based interactive modules of this book were developed with you, the student, in mind. Take the time to use them in conjunction with the material in the textbook. Video animations can show you how fields and waves propagate in time and space, how the beam of an antenna array can be made to scan electronically, and examples of how current is induced in a circuit under the influence of a changing magnetic field. The modules are a useful resource for self-study. You can find them at the Student Website link on http://www.pearsonhighered.com/ulaby. Use them!

ACKNOWLEDGMENTS

Special thanks are due to reviewers for their valuable comments and suggestions. They include Constantine Balanis of Arizona State University, Harold Mott of the University of Alabama, David Pozar of the University of Massachusetts, S. N. Prasad of Bradley University, Robert Bond of New Mexico Institute of Technology, Mark Robinson of the University of Colorado at Colorado Springs, and Raj Mittra of the University of Illinois. I appreciate the dedicated efforts of the staff at Prentice Hall and I am grateful for their help in shepherding this project through the publication process in a very timely manner.

Fawwaz T. Ulaby



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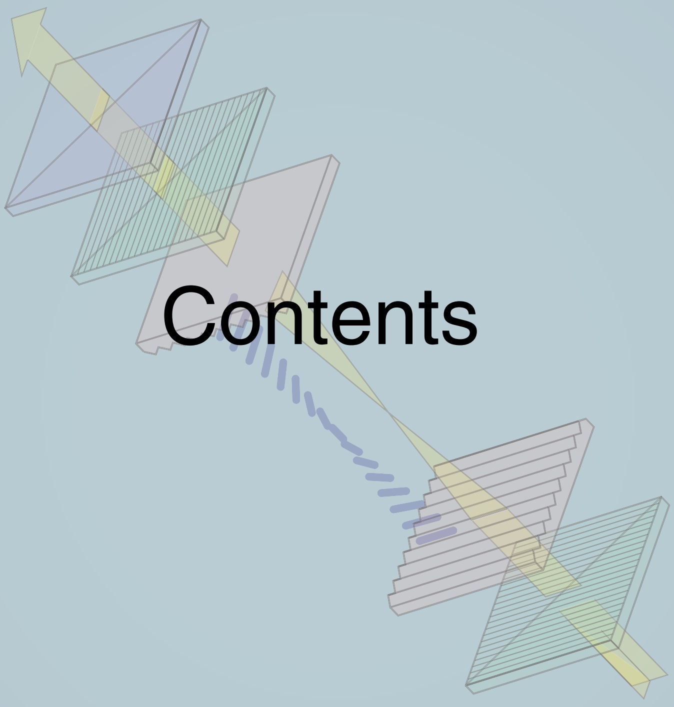

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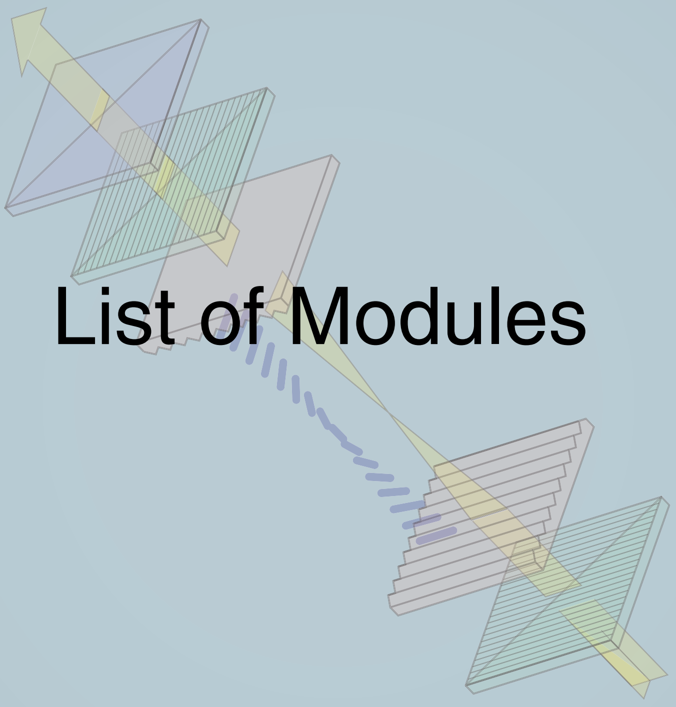

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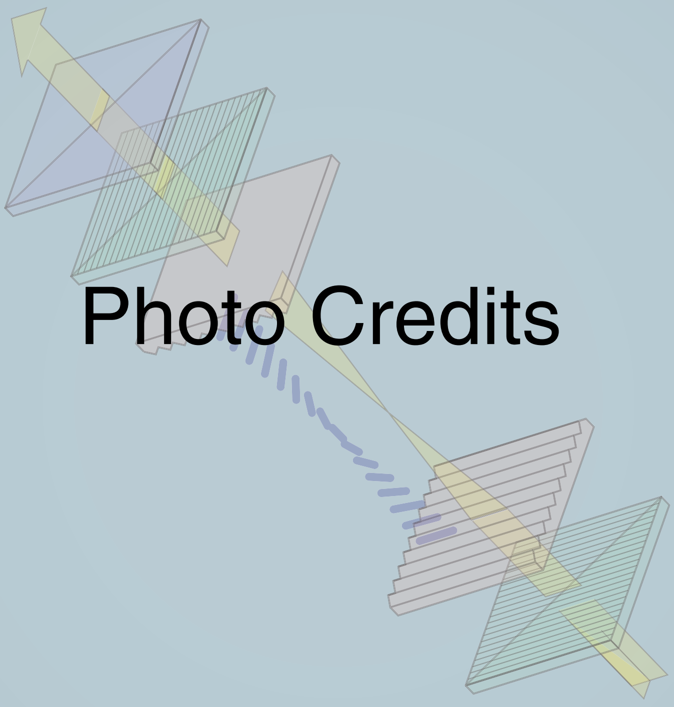

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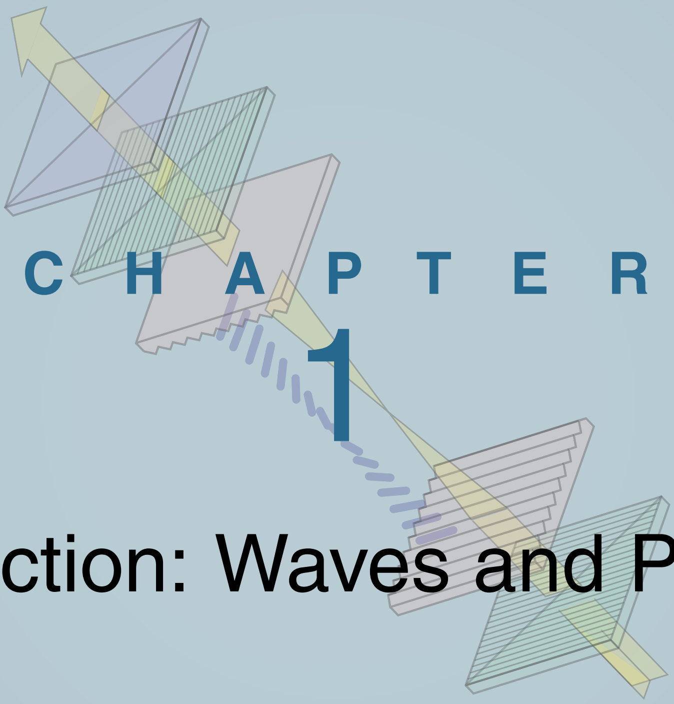

CHAPTER

1

Introduction: Waves and Phasors

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Objectives

Upon learning the material presented in this chapter, you should be able to:

1. Describe the basic properties of electric and magnetic forces.
2. Ascribe mathematical formulations to sinusoidal waves traveling in both lossless and lossy media.
3. Apply complex algebra in rectangular and polar forms.
4. Apply the phasor-domain technique to analyze circuits driven by sinusoidal sources.

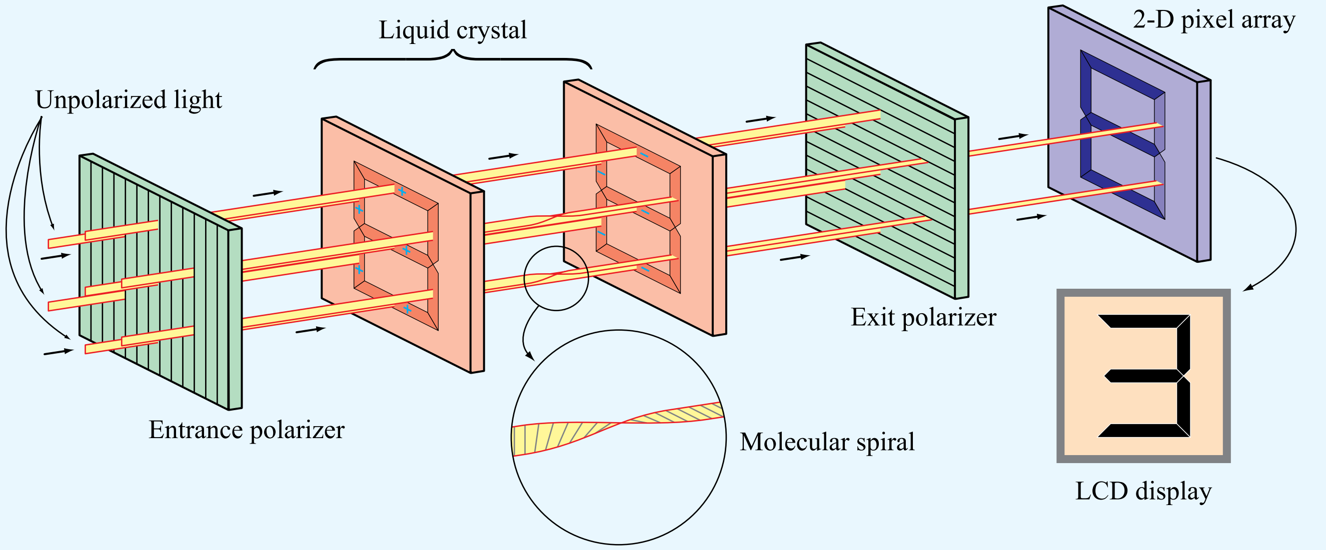


Figure 1-1 2-D LCD array.

Overview

Liquid crystal displays have become integral parts of many electronic consumer products, ranging from alarm clocks and cell phones to laptop computers and television systems. LCD technology relies on special electrical and optical properties of a class of materials known as ***liquid crystals***, which are neither pure solids nor pure liquids but rather a hybrid of both. The molecular structure of these materials is such that when light travels through them, the polarization of the emerging light depends on whether or not a voltage exists across the material. Consequently, when no voltage is applied, the exit surface appears bright, and conversely, when a voltage of a certain level is applied across the LCD material, no light passes through it, resulting in a dark pixel. In-between voltages translate into a range of grey levels. By controlling the voltages across individual pixels in a two-dimensional array, a complete image can be displayed (**Fig. 1-1**). Color displays are composed of three subpixels with red, green, and blue filters.

> ▶ The polarization behavior of light in an LCD is a prime example of how electromagnetics is at the heart of electrical and computer engineering. ◀

The subject of this book is applied electromagnetics (EM), which encompasses the study of both static and dynamic electric and magnetic phenomena and their engineering applications. Primary emphasis is placed on the fundamental properties of dynamic (time-varying) electromagnetic fields because of their greater relevance to practical problems in many applications, including wireless and optical communications, radar, bioelectromagnetics, and high-speed microelectronics. We study wave propagation in guided media, such as coaxial transmission lines, optical fibers and waveguides; wave reflection and transmission at interfaces between dissimilar media; radiation by antennas; and several other related topics. The concluding chapter is intended to illustrate a few aspects of applied EM through an examination of design considerations associated with the use and operation of radar sensors and satellite communication systems.

We begin this chapter with a chronology of the history of electricity and magnetism. Next, we introduce the fundamental electric and magnetic field quantities of electromagnetics, as well as their relationships to each other and to the electric charges and currents that generate them. These relationships constitute the underpinnings of the study of electromagnetic phenomena. Then, in preparation for the material presented in Chapter 2, we provide short reviews of three topics: traveling waves, complex numbers, and phasors, all useful in solving time-harmonic problems.

1-1 Historical Timeline

The history of EM may be divided into two overlapping eras. In the ***classical era***, the fundamental laws of electricity and magnetism were discovered and formulated. Building on these formulations, the ***modern era*** of the past 100 years ushered in the birth of the field of applied EM, the topic of this book.

1-1.1 EM in the Classical Era

Chronology 1-1 provides a timeline for the development of electromagnetic theory in the classical era. It highlights those discoveries and inventions that have impacted the historical development of EM in a very significant way, even though the selected discoveries represent only a small fraction of those responsible for our current understanding of electromagnetics. As we proceed through the book, some of the names highlighted in Chronology 1-1, such as those of Coulomb and Faraday, will appear again later as we discuss the laws and formulations named after them.

The attractive force of magnetite was reported by the Greeks some 2800 years ago. It was also a Greek, ***Thales of Miletus***, who first wrote about what we now call static electricity: he described how rubbing amber caused it to develop a force that could pick up light objects such as feathers. The term "*electric*" first appeared in print around 1600 in a treatise on the (electric) force generated by friction, authored by the physician to Queen Elizabeth I, ***William Gilbert***.

About a century later, in 1733, ***Charles-François du Fay*** introduced the notion that electricity involves two types of "fluids," one "positive" and the other "negative," and that like-fluids repel and opposite-fluids attract. His notion of a fluid is what we today call electric charge. The invention of the capacitor in 1745, originally called the ***Leyden jar***, made it possible to store significant amounts of electric charge in a single device. A few years later, in 1752, ***Benjamin Franklin*** demonstrated that lightning is a form of electricity. He transferred electric charge from a cloud to a Leyden jar via a silk kite flown in a thunderstorm. The collective eighteenth-century knowledge about electricity was integrated in 1785 by ***Charles-Augustin de Coulomb***, in the form of a mathematical formulation characterizing the electrical force between two charges in terms of their strengths and polarities and the distance between them.

The year 1800 is noted for the development of the first electric battery by ***Alessandro Volta***, and 1820 was a banner year for discoveries about how electric currents induce magnetism. This knowledge was put to good use by ***Joseph Henry***, who developed one of the earliest electromagnets and dc (direct current) electric motors. Shortly thereafter, ***Michael Faraday*** built the first electric generator (the converse of the electric motor). Faraday, in essence, demonstrated that a changing magnetic field induces an electric field (and hence a voltage). The converse relation, namely that a changing electric field induces a magnetic field, was first proposed by ***James Clerk Maxwell*** in 1864 and then incorporated into his four (now) famous equations in 1873.

► Maxwell's equations represent the foundation of classical electromagnetic theory. ◄

Maxwell's theory, which predicted the existence of electromagnetic waves, was not fully accepted by the scientific community at that time, not until verified experimentally by means of radio waves by ***Heinrich Hertz*** in the 1880s. X-rays, another member of the EM family, were discovered in 1895 by ***Wilhelm Röntgen***. In the same decade, ***Nikola Tesla*** was the first to develop the ac (alternating current) motor, considered a major advance over its predecessor, the dc motor.

Despite the advances made in the 19th century in our understanding of electricity and magnetism and how to put them to practical use, it was not until 1897 that the fundamental carrier of electric charge, the electron, was identified and its properties quantified by ***Joseph Thomson***. The ability to eject electrons from a material by shining electromagnetic energy, such as light, on it is known as the ***photoelectric effect***.

► To explain the photoelectric effect, ***Albert Einstein*** adopted the quantum concept of energy that had been advanced a few years earlier (1900) by ***Max Planck***. Symbolically, this step represents the bridge between the classical and modern eras of electromagnetics. ◄

1-1.2 EM in the Modern Era

Electromagnetics plays a role in the design and operation of every conceivable electronic device, including the diode, transistor, integrated circuit, laser, display screen, bar-code reader, cell phone, and microwave oven, to name but a few. Given the breadth and diversity of these applications (**Fig. 1-2**), it is far more difficult to construct a meaningful timeline for the modern era than for the classical era. That said, one can develop timelines for specific technologies and link their milestone innovations to EM. Chronologies 1-2 and 1-3 present timelines for the development of telecommunications and computers,

Chronology 1-1: TIMELINE FOR ELECTROMAGNETICS IN THE CLASSICAL ERA

Electromagnetics in the Classical Era

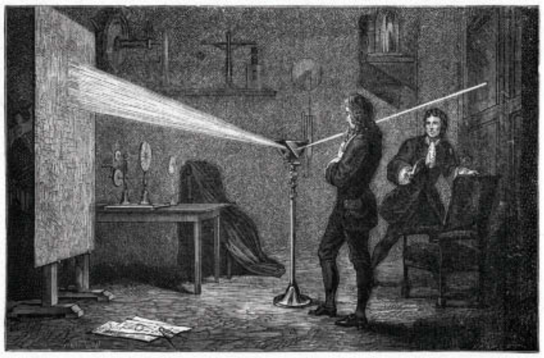
ca. 900 BC Legend has it that while walking across a field in northern Greece, a shepherd named Magnus experiences a pull on the iron nails in his sandals by the black rock he is standing on. The region was later named Magnesia and the rock became known as magnetite [a form of iron with permanent magnetism].

ca. 600 BC Greek philosopher **Thales** describes how amber, after being rubbed with cat fur, can pick up feathers [static electricity].

ca. 1000 Magnetic compass used as a navigational device.

1600 **William Gilbert** (English) coins the term electric after the Greek word for amber (*elektron*), and observes that a compass needle points north-south because the Earth acts as a bar magnet.

1671 **Isaac Newton** (English) demonstrates that white light is a mixture of all the colors.



1733 **Charles-François du Fay** (French) discovers that electric charges are of two forms, and that like charges repel and unlike charges attract.

1745 **Pieter van Musschenbroek** (Dutch) invents the Leyden jar, the first electrical capacitor.

1752 **Benjamin Franklin** (American) invents the lightning rod and demonstrates that lightning is electricity.

1785 **Charles-Augustin de Coulomb** (French) demonstrates that the electrical force between charges is proportional to the inverse of the square of the distance between them.

1800 **Alessandro Volta** (Italian) develops the first electric battery.

1820 **Hans Christian Oersted** (Danish) demonstrates the interconnection between electricity and magnetism through his discovery that an electric current in a wire causes a compass needle to orient itself perpendicular to the wire.

1820 **Andre-Marie Ampère** (French) notes that parallel currents in wires attract each other and opposite currents repel.

1820 **Jean-Baptiste Biot** (French) and **Félix Savart** (French) develop the Biot-Savart law relating the magnetic field induced by a wire segment to the current flowing through it.

Chronology 1-1: TIMELINE FOR ELECTROMAGNETICS IN THE CLASSICAL ERA (continued)

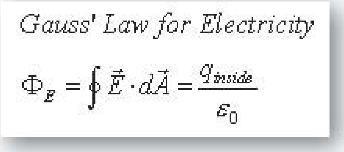
Electromagnetics in the Classical Era

1827 **Georg Simon Ohm** (German) formulates Ohm's law relating electric potential to current and resistance.

1827 **Joseph Henry** (American) introduces the concept of inductance, and builds one of the earliest electric motors. He also assisted Samual Morse in the development of the telegraph.

1831 **Michael Faraday** (English) discovers that a changing magnetic flux can induce an electromotive force.

1835 **Carl Friedrich Gauss** (German) formulates Gauss's law relating the electric flux flowing through an enclosed surface to the enclosed electric charge.



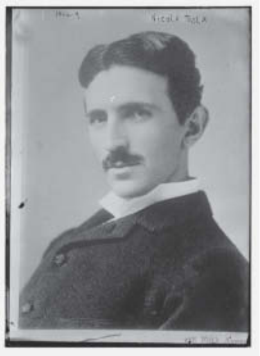
Gauss' Law for Electricity

$$\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{q_{inside}}{\varepsilon_0}$$

1873 **James Clerk Maxwell** (Scottish) publishes his Treatise on Electricity and Magnetism in which he unites the discoveries of Coulomb, Oersted, Ampère, Faraday, and others into four elegantly constructed mathematical equations, now known as Maxwell's Equations.

1887 **Heinrich Hertz** (German) builds a system that can generate electromagnetic waves (at radio frequencies) and detect them.

1888 **Nikola Tesla** (Croatian-American) invents the ac (alternating current) electric motor.



1895 **Wilhelm Röntgen** (German) discovers X-rays. One of his first X-ray images was of the bones in his wife's hands. [1901 Nobel prize in physics.]

1897 **Joseph John Thomson** (English) discovers the electron and measures its charge-to-mass ratio. [1906 Nobel prize in physics.]

1905 **Albert Einstein** (German-American) explains the photoelectric effect discovered earlier by Hertz in 1887. [1921 Nobel prize in physics.]