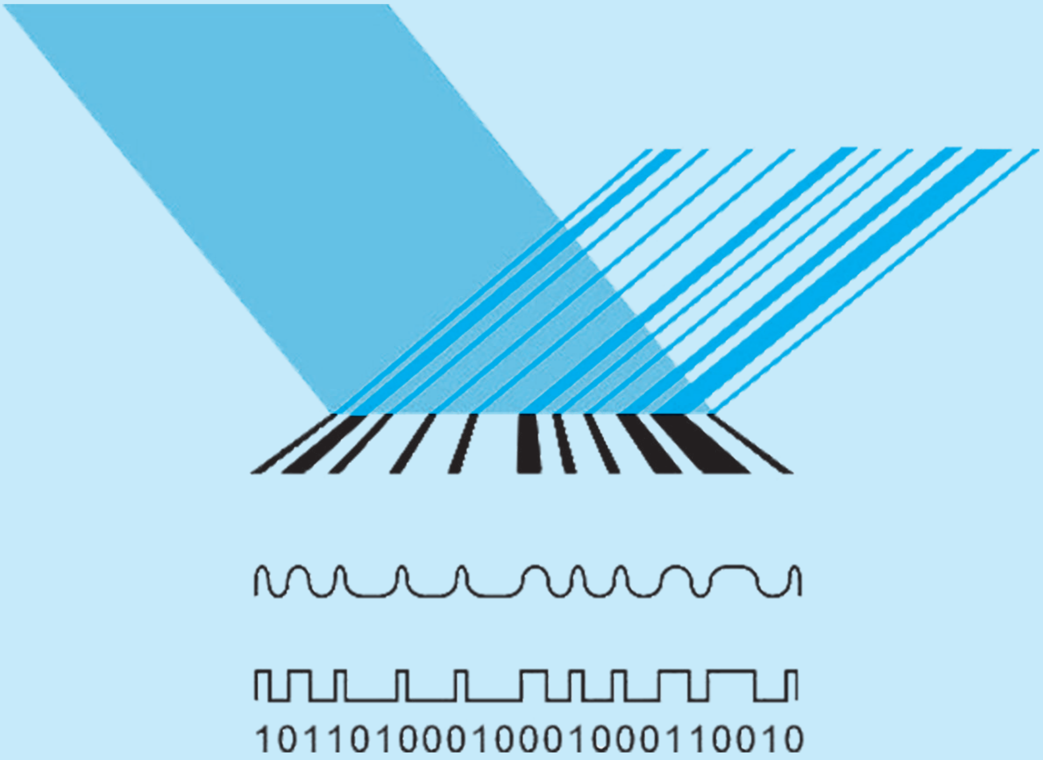
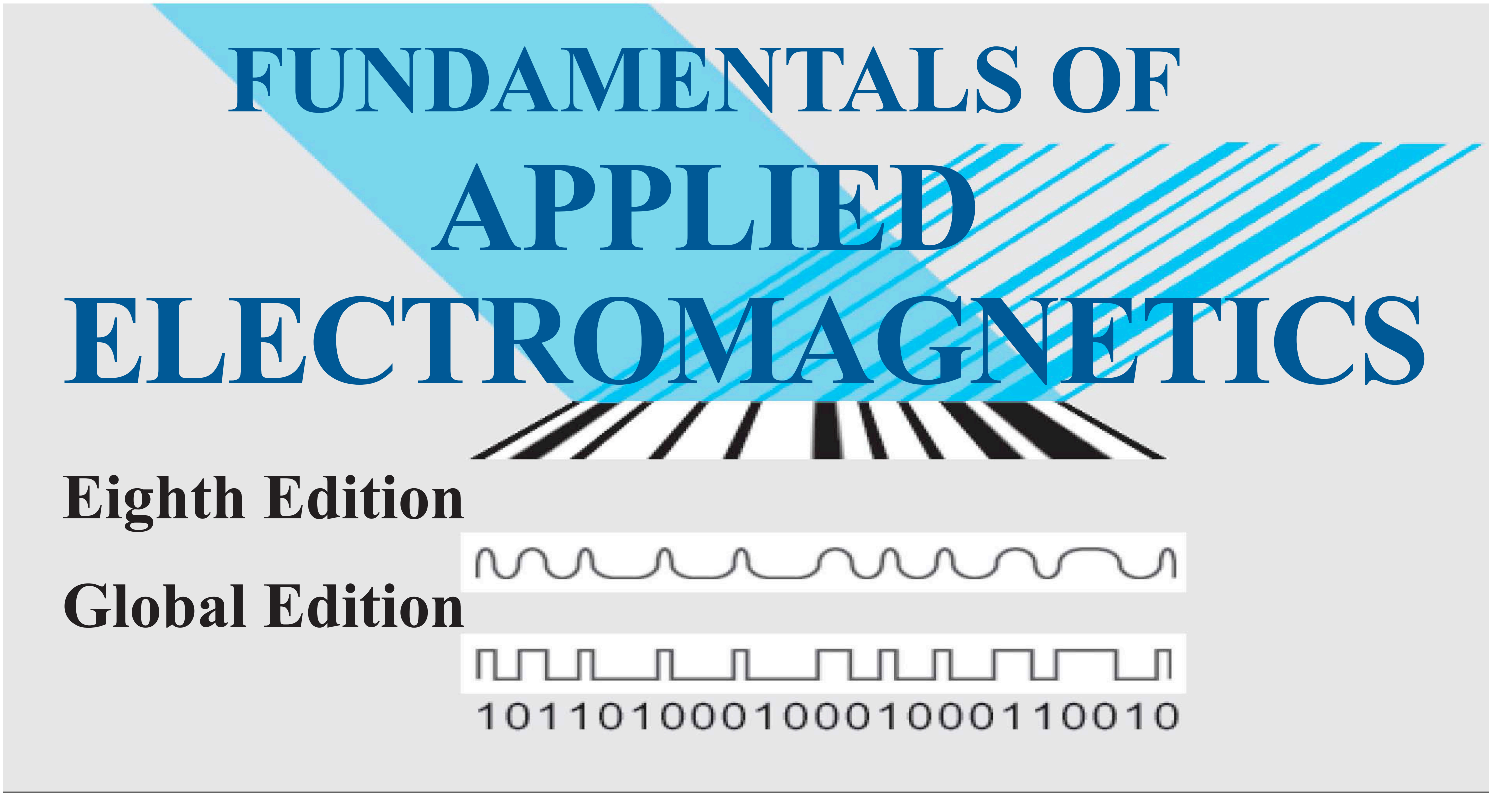
GLOBAL
EDITION

Fundamentals of Applied Electromagnetics

EIGHTH EDITION

Fawwaz T. Ulaby
Umberto Ravaioli





FUNDAMENTALS OF APPLIED ELECTROMAGNETICS

Eighth Edition

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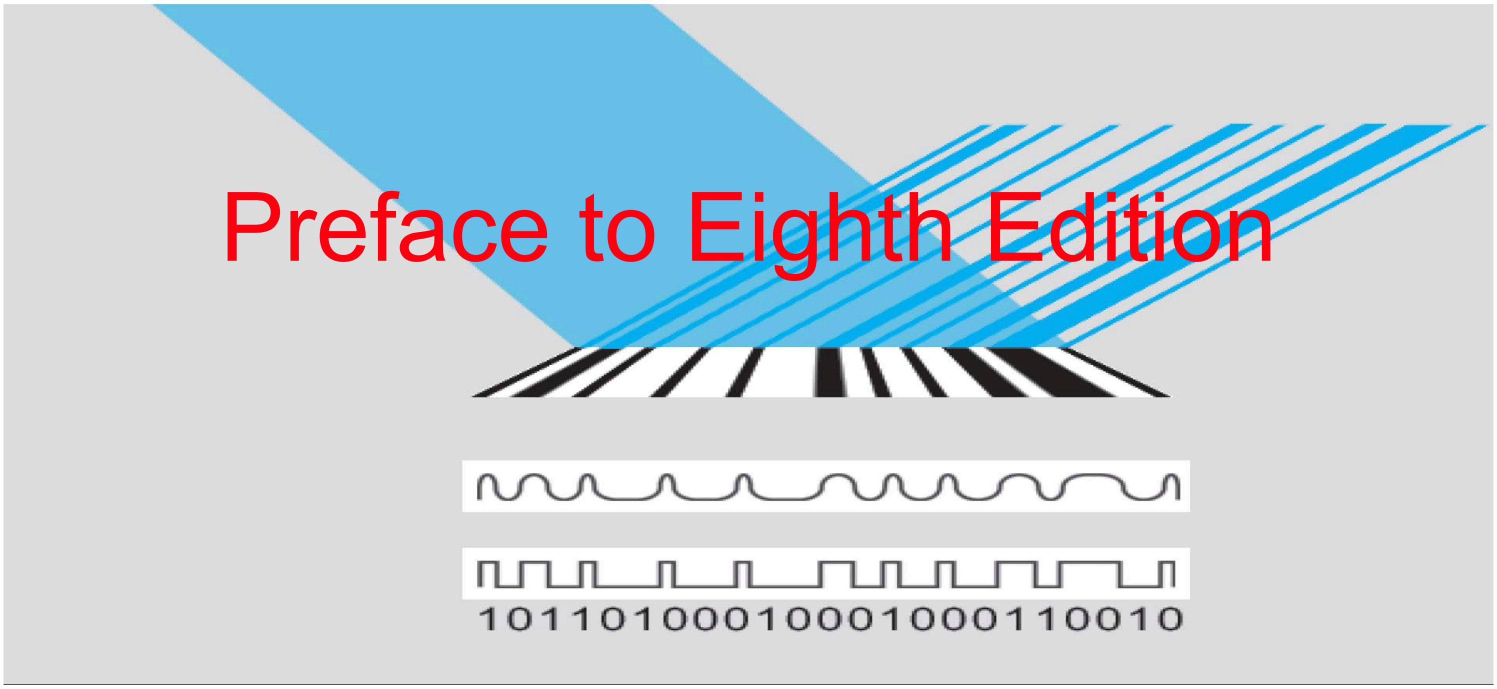
We dedicate this book to
Jean and Ann Lucia.

Preface to Eighth Edition



Building on the core content and style of its predecessor, this eighth edition (8/e) of *Applied Electromagnetics* includes features designed to help students develop deep 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.

NEW TO THIS EDITION

- Additional exercises
- Updated Technology Briefs
- Enhanced figures and images
- New/updated end-of-chapter problems

* The interactive modules and Technology Briefs can be found at the book companion website: **em8e.eecs.umich.edu**.

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

This 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 will use 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 this 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. These chapters will provide the student with an overall framework for what is to come and show 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 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 this book with 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 options.

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

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. The multiple-window feature of electronic displays makes it possible to design interactive modules with "help" buttons to guide you through the solution of a problem when needed. 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 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 book companion website **em8e.eecs.umich.edu**. Use them!

BOOK COMPANION WEBSITE

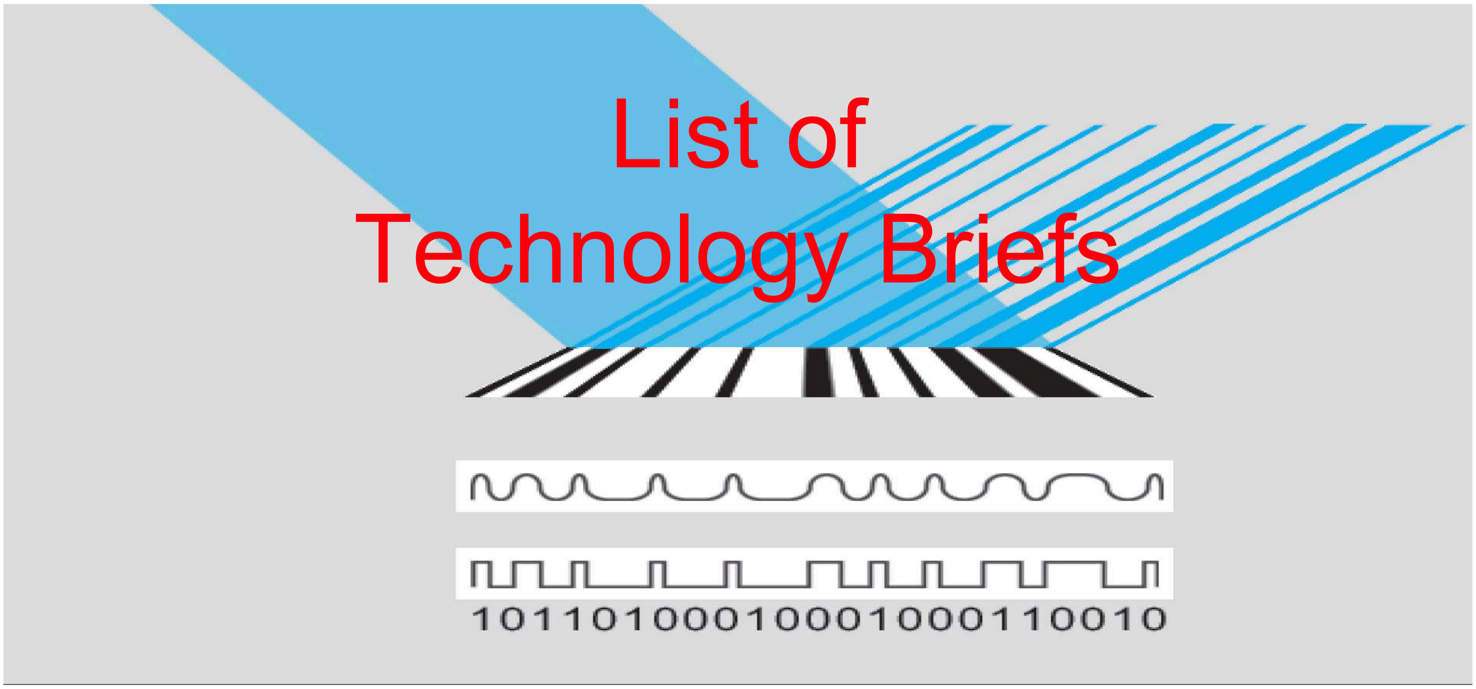
Throughout the book, we use the symbol EM to denote the book companion website **em8e.eecs.umich.edu**, which contains a wealth of information and tons of useful tools.

ACKNOWLEDGMENTS

Special thanks are due to our 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 the 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

List of Technology Briefs



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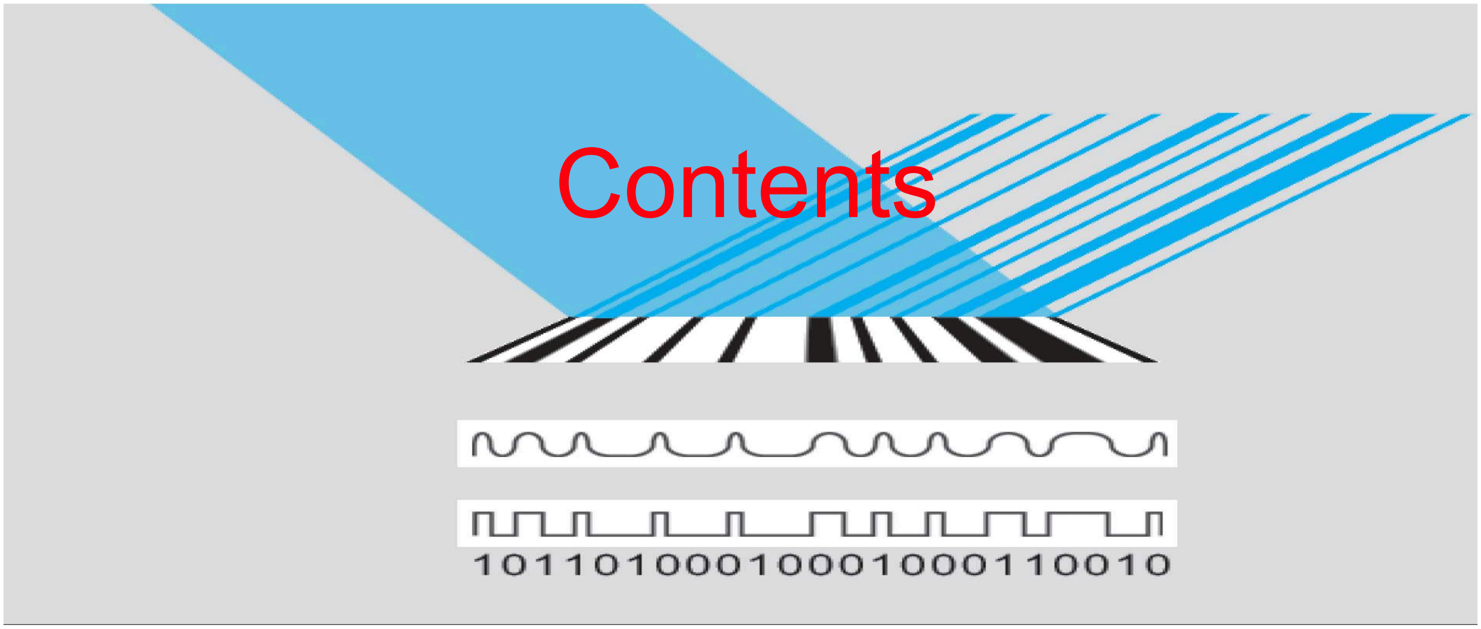

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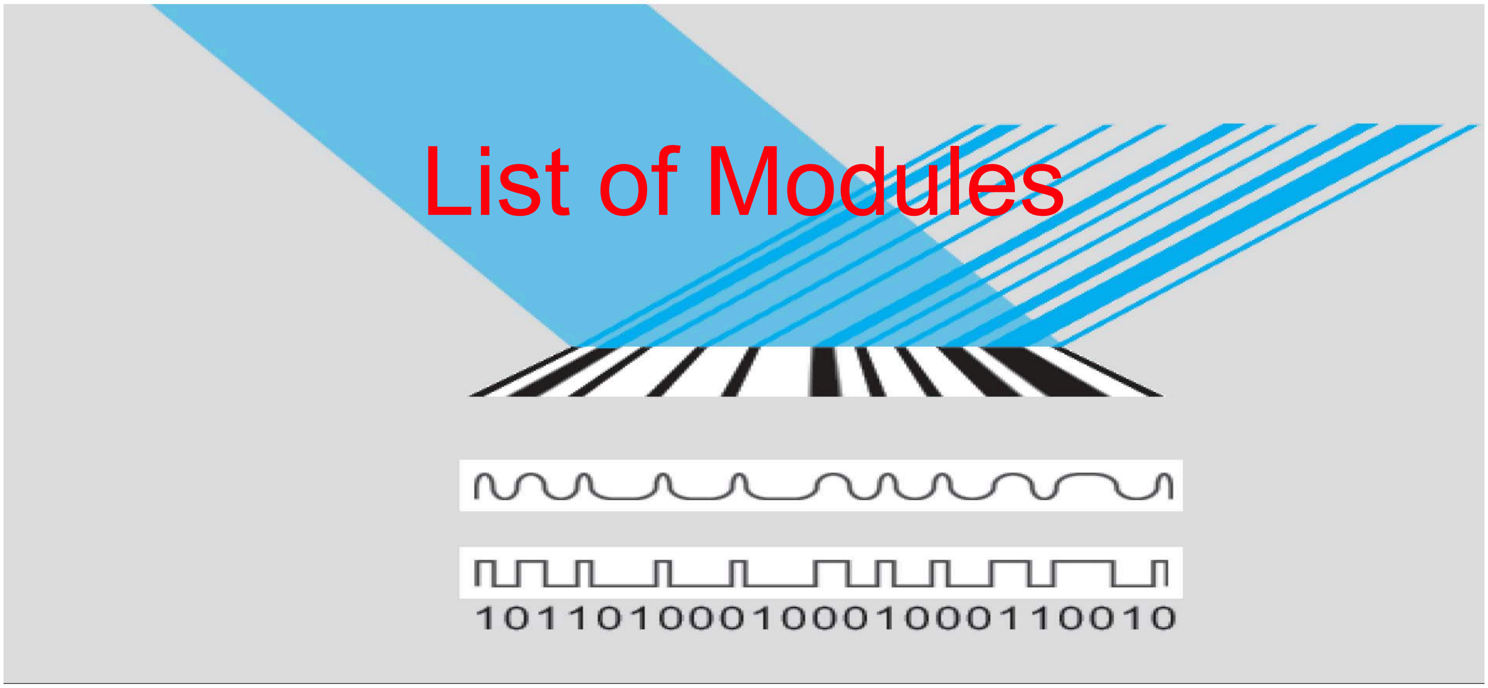

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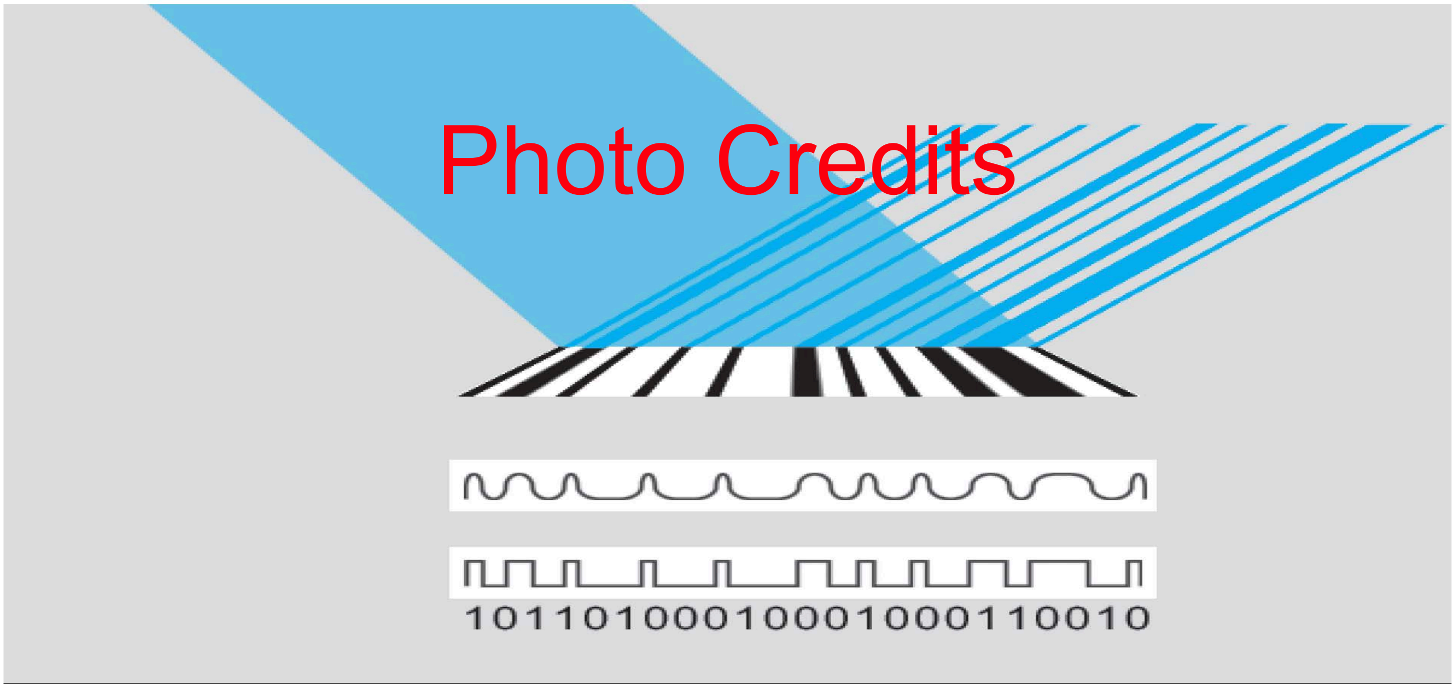

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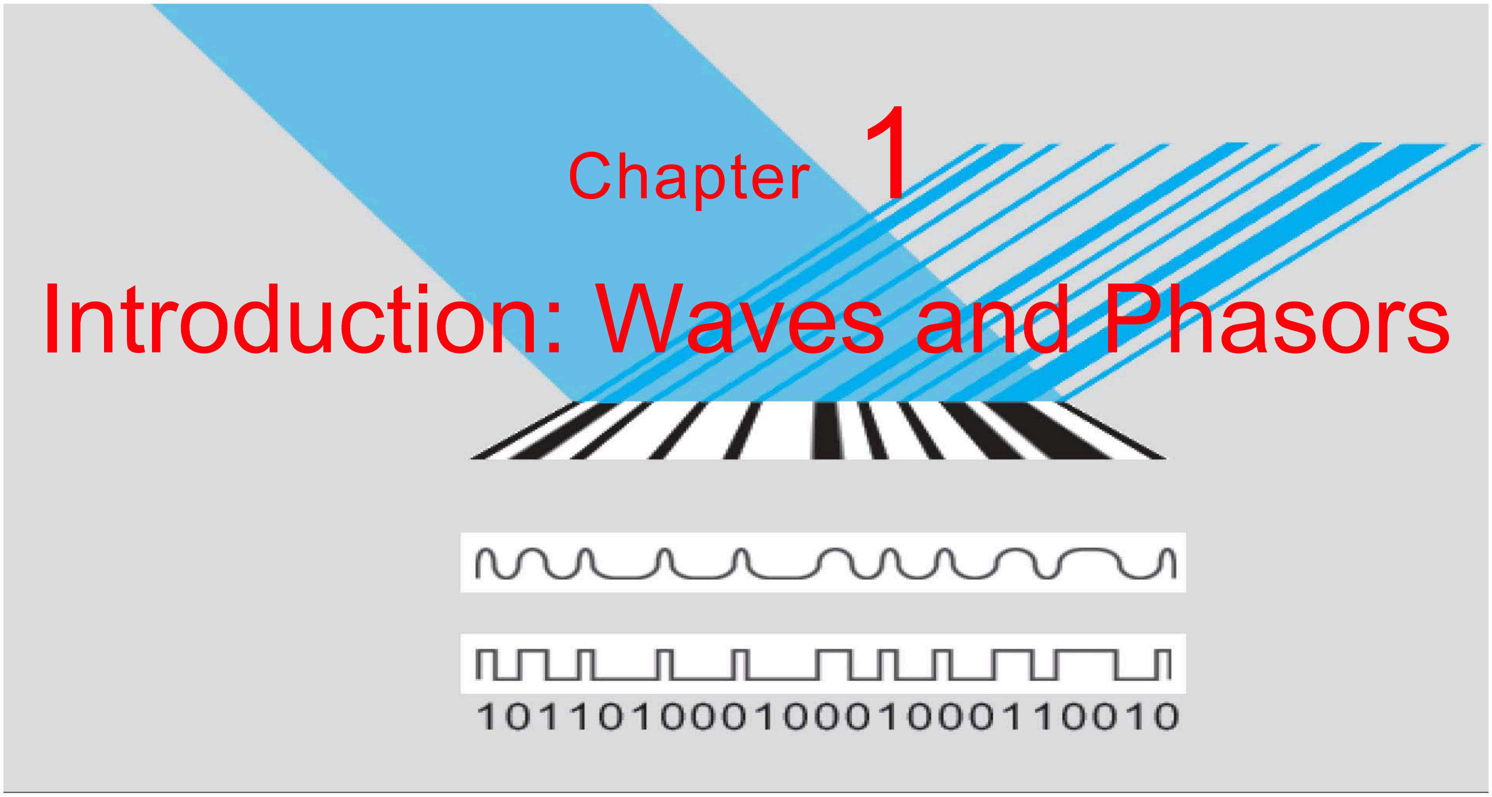
Chapter 1

Introduction: Waves and Phasors



Chapter Contents

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.

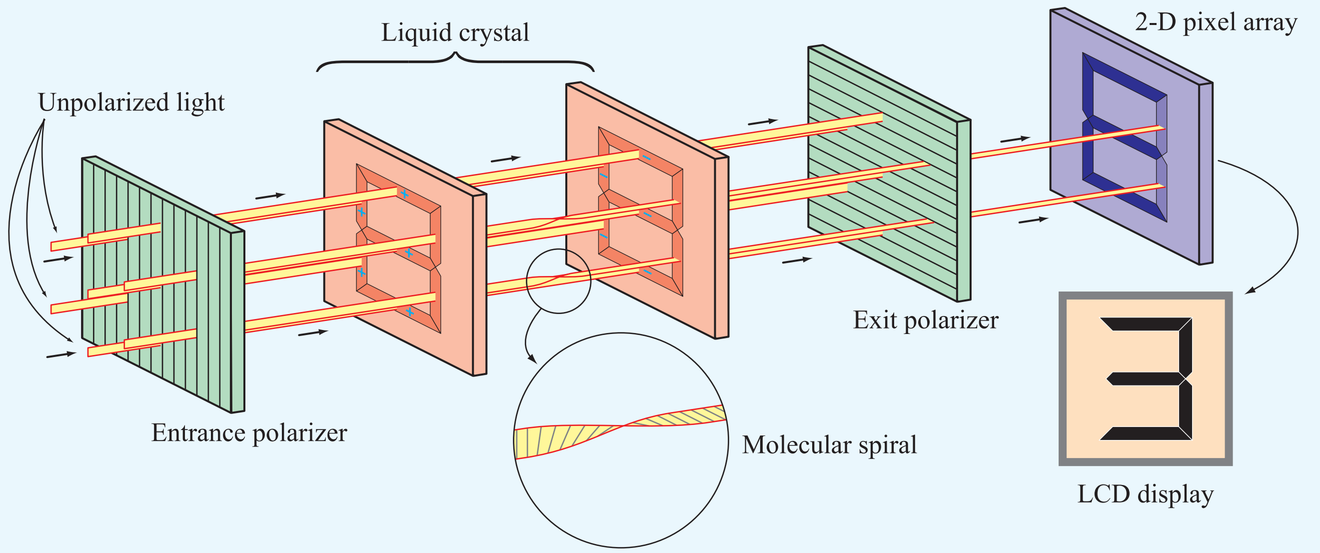


Figure 1-1 2-D LCD array.

Overview

Liquid crystal displays (***LCDs***) 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. 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 a 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 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, which are all useful in solving time-harmonic problems.

1-1 Historical Timeline

The history of EM may be divided into two overlapping eras. The first is the ***classical era***, during which 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 as we know it today.

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 this book, some of the names highlighted in Chronology 1-1, such as those of Coulomb and Faraday, will appear again 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. It was later 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 motor, which was 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 play 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, technologies that have become integral parts of today's societal infrastructure. Some of the entries in these chronologies refer to specific inventions, such as the telegraph, the transistor, and the laser. The operational principles and capabilities of some of these technologies are highlighted in special sections called *Technology Briefs* that are scattered throughout this book.

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, which was 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	**André-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.

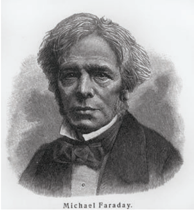
Chronology 1-1: TIMELINE FOR ELECTROMAGNETICS IN THE CLASSICAL ERA (continued)

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.

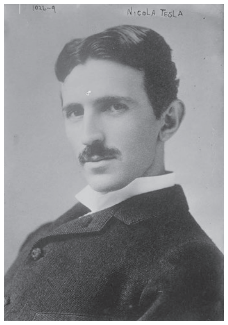
Gauss' Law for Electricity

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

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.

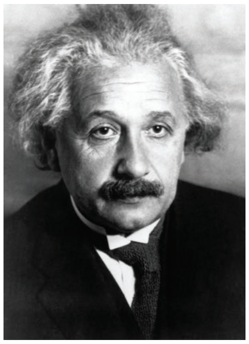
1888 **Nikola Tesla** (American) invents the ac (alternating current) electric motor.



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.]

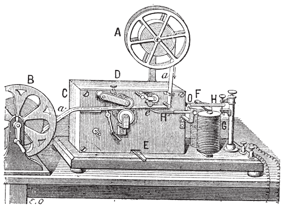
1905 **Albert Einstein** (German-American) explains the photoelectric effect discovered earlier by Hertz in 1887. [1921 Nobel prize in physics.]



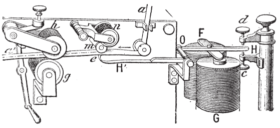
Chronology 1-2: TIMELINE FOR TELECOMMUNICATIONS

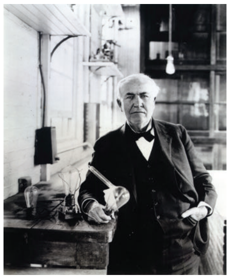
Telecommunications

1825 **William Sturgeon** (English) develops the multiturn electromagnet.



1837 **Samuel Morse** (American) patents the electromagnetic telegraph using a code of dots and dashes to represent letters and numbers.





1872 **Thomas Edison** (American) patents the electric typewriter.

1876 **Alexander Graham Bell** (Scottish-American) invents the telephone. The rotary dial becomes available in 1890, and by 1900, telephone systems are installed in many communities.

1887 **Heinrich Hertz** (German) generates radio waves and demonstrates that they share the same properties as light.

1887 **Emil Berliner** (American) invents the flat gramophone disc, or record.

1896 **Guglielmo Marconi** (Italian) files his first of many patents on wireless transmission by radio. In 1901, he demonstrates radio telegraphy across the Atlantic Ocean. [1909 Nobel prize in physics, shared with Karl Braun (German).]

1897 **Karl Braun** (German) invents the cathode ray tube (CRT). [1909 Nobel prize in physics, shared with Marconi.]

1902 **Reginald Fessenden** (American) invents amplitude modulation for telephone transmission. In 1906, he introduces AM radio broadcasting of speech and music on Christmas Eve.

1912 **Lee De Forest** (American) develops the triode tube amplifier for wireless telegraphy. Also in 1912, the wireless distress call issued by the Titanic was heard 58 miles away by the ocean liner Carpathia, which managed to rescue 705 Titanic passengers 3.5 hours later.

1919 **Edwin Armstong** (American) invents the superheterodyne radio receiver.

1920 Birth of commercial radio broadcasting; Westinghouse establishes radio station KDKA in Pittsburgh, Pennsylvania.

Chronology 1-2: TIMELINE FOR TELECOMMUNICATIONS (continued)

Telecommunications

1923

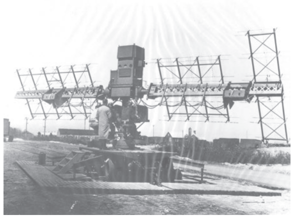
Vladimir Zworykin (Russian-American) invents television. In 1926, **John Baird** (Scottish) transmits TV images over telephone wires from London to Glasgow. Regular TV broadcasting began in Germany (1935), England (1936), and the United States (1939).

1926 Transatlantic telephone service between London and New York.

1932 First microwave telephone link, installed (by Marconi) between Vatican City and the Pope's summer residence.

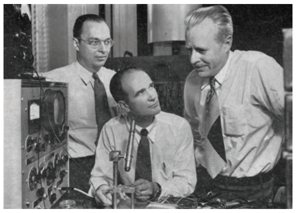
1933 **Edwin Armstrong** (American) invents frequency modulation (FM) for radio transmission.

1935 **Robert Watson-Watt** (Scottish) invents radar.



1938 **H. A. Reeves** (American) invents pulse code modulation (PCM).

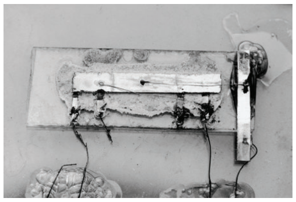
1947 **William Shockley**, **Walter Brattain**, and **John Bardeen** (all Americans) invent the junction transistor at Bell Labs [1956 Nobel prize in physics].



1955 Pager is introduced as a radio communication product in hospitals and factories.

1955 **Narinder Kapany** (Indian-American) demonstrates the optical fiber as a low-loss, light-transmission medium.

1958 **Jack Kilby** (American) builds first integrated circuit (IC) on germanium and, independently, **Robert Noyce** (American) builds first IC on silicon.



1960

Echo, the first passive communication satellite, is launched and successfully reflects radio signals back to Earth. In 1963, the first communication satellite is placed in geosynchronous orbit.

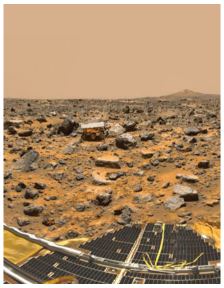
1969 ARPANET is established by the U.S. Department of Defense and will evolve later into the Internet.

1979 Japan builds the first cellular telephone network:
- 1983: Cellular phone networks start in the United States.
- 1990: Electronic beepers become common.
- 1995: Cell phones become widely available.
- 2002: Cell phone supports video and Internet.

1984 Worldwide Internet becomes operational.

1988 First transatlantic optical fiber cable deployed between the U.S. and Europe.

1997 The Mars Pathfinder sends images to Earth.



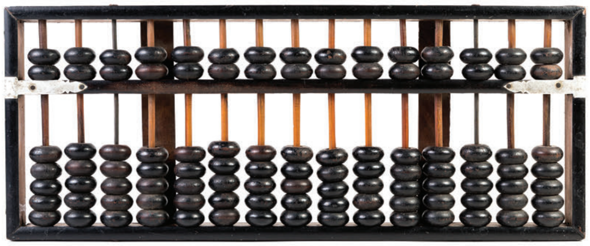
2004 Wireless communication is supported by many airports, university campuses, and other facilities.

2012 Smartphones worldwide exceed 1 billion.

Chronology 1-3: TIMELINE FOR COMPUTER TECHNOLOGY

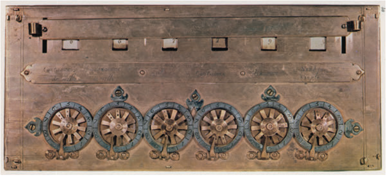
Computer Technology

ca 1100 BC The abacus is the earliest known calculating device.



1614 **John Napier** (Scottish) develops the logarithm system.

1642 **Blaise Pascal** (French) builds the first adding machine using multiple dials.

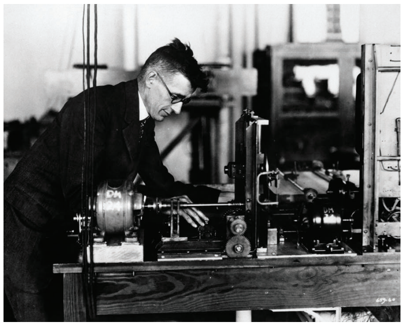


1671 **Gottfried von Leibniz** (German) builds calculator that can do both addition and multiplication.

1820 **Charles Xavier Thomas de Colmar** (French) builds the Arithmometer: the first mass-produced calculator.

1885 **Dorr Felt** (American) invents and markets a key-operated adding machine (and adds a printer in 1889).

1930 **Vannevar Bush** (American) develops the differential analyzer, which is an analog computer for solving differential equations.



1941 **Konrad Zuze** (German) develops the first programmable digital computer, making use of binary arithmetic and electric relays.

1945 **John Mauchly** and **J. Presper Eckert** (both American) develop the ENIAC, which is the first all-electronic computer.

1950 **Yoshiro Nakama** (Japanese) patents the floppy disk as a magnetic medium for storing data.

1956 **John Backus** (American) develops FORTRAN, which is the first major programming language.

```
C       FORTRAN PROGRAM FOR
PRINTING A TABLE OF CUBES
        DO 5  I = 1, 64
        ICUBE = I * I * I
        PRINT 2, I, ICUBE
     2  FORMAT (1H , I3,I7)
     5  CONTINUE
        STOP
```

1958 Bell Labs develops the modem.

1960 Digital Equipment Corporation introduces the first minicomputer, the PDP-1, to be followed with the PDP-8 in 1965.

1964 IBM's 360 mainframe becomes the standard computer for major businesses.

1965 **John Kemeny** and **Thomas Kurtz** (both American) develop the BASIC computer language.

```
PRINT
FOR Counter = 1TO Items
   PRINTUSING "##."; Counter;
    LOCATE , ItemColumn
    PRINTItem$(Counter);
    LOCATE , PriceColumn
  PRINTPrice$(Counter)
NEXT Counter
```

Chronology 1-3: TIMELINE FOR COMPUTER TECHNOLOGY (continued)

Computer Technology

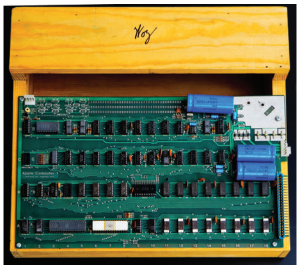
1968 **Douglas Engelbart** (American) demonstrates a word-processor system, the mouse pointing device and the use of “windows.”

1971 Texas Instruments introduces the pocket calculator.

1971 **Ted Hoff** (American) invents the Intel 4004, which is the first computer microprocessor.

1976 IBM introduces the laser printer.

1976 Apple Computer sells Apple I in kit form, which is followed by the fully assembled Apple II in 1977 and the Macintosh in 1984.



1980 Microsoft introduces the MS-DOS computer disk operating system. Microsoft Windows is marketed in 1985.

1981 IBM introduces the PC.

1989 **Tim Berners-Lee** (British) invents the World Wide Web by introducing a networked hypertext system.

1991 The internet connects to 600,000 hosts in more than 100 countries.

1995 Sun Microsystems introduces the Java programming language.

1996 **Sabeer Bhatia** (Indian-American) and **Jack Smith** (American) launch Hotmail, which is the first webmail service.

1997 IBM’s Deep Blue computer defeats World Chess Champion Garry Kasparov.

2002 The billionth personal computer is sold; the second billion is reached in 2007.

2010 The iPad is introduced in 2010.

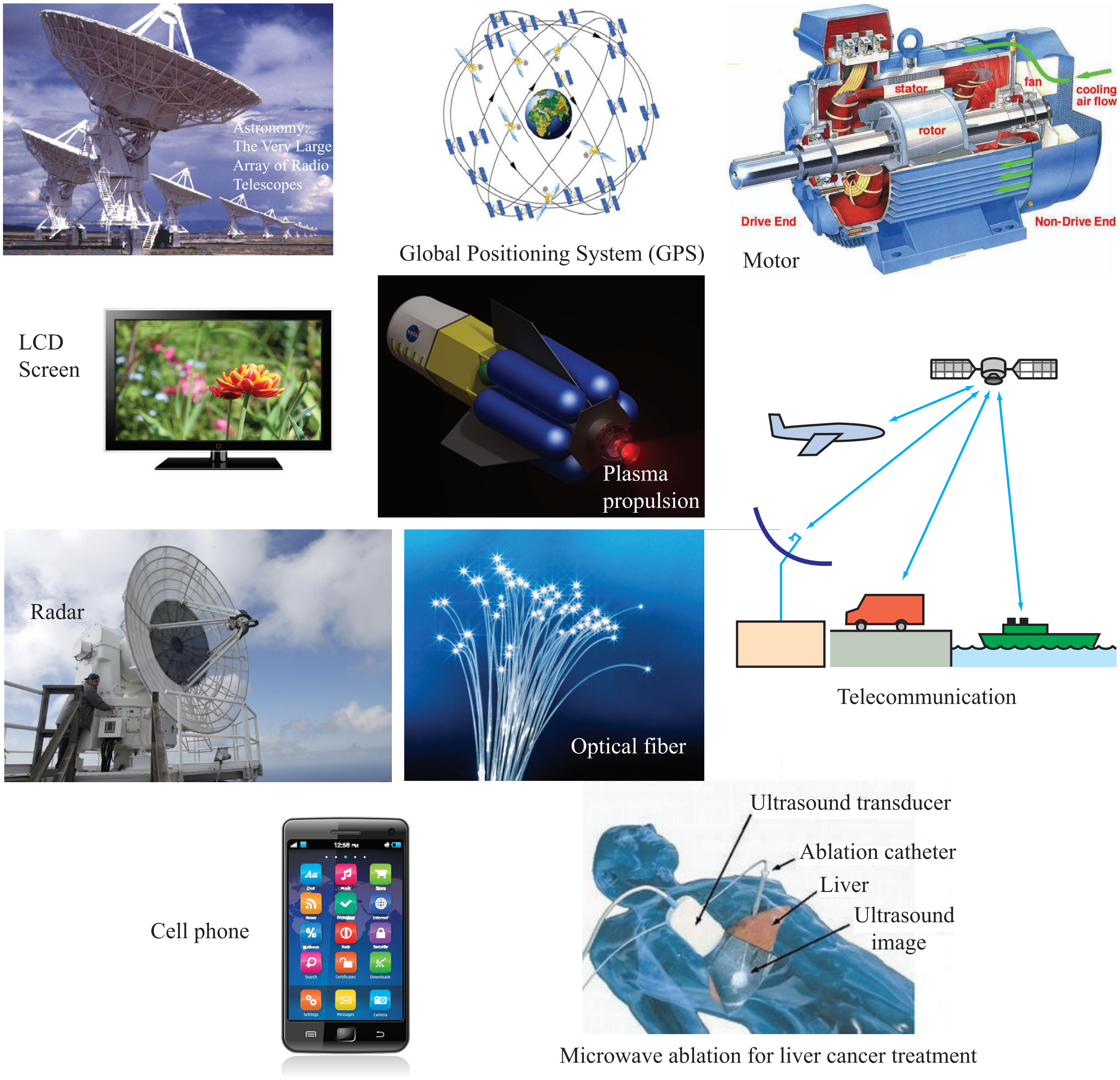


Figure 1-2 Electromagnetics is at the heart of numerous systems and applications.

Table 1-1 **Fundamental SI units.**

Dimension	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric charge	coulomb	C
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

1-2 Dimensions, Units, and Notation

The ***International System of Units***, abbreviated ***SI*** after its French name *Système Internationale*, is the standard system used in today's scientific literature for expressing the units of physical quantities. Length is a ***dimension*** and meter is the ***unit*** by which it is expressed relative to a reference standard. The SI system is based on the units for the seven ***fundamental dimensions*** listed in **Table 1-1**. The units for all other dimensions are regarded as ***secondary*** because they are based on, and can be expressed in terms of, the seven fundamental units. Appendix A contains a list of quantities used in this book, together with their symbols and units.

For quantities ranging in value between 10^{-18} and 10^{18}, a set of prefixes arranged in steps of 10^3 are commonly used to denote multiples and submultiples of units. These prefixes, all of which were derived from Greek, Latin, Spanish, and Danish terms, are listed in **Table 1-2**. A length of 5×10^{-9} m, for example, may be written as 5 nm.

In EM, we work with scalar and vector quantities. In this book, we use a medium-weight italic font for symbols denoting scalar quantities, such as R for resistance, and a boldface roman font for symbols denoting vectors, such as $\mathbf{E}$ for the electric field vector. A vector consists of a magnitude (scalar) and a direction, with the direction usually denoted by a unit vector. For example,

$$\mathbf{E} = \hat{\mathbf{x}}E, \tag{1.1}$$

where E is the magnitude of $\mathbf{E}$ and $\hat{\mathbf{x}}$ is its direction. A symbol denoting a unit vector is printed in boldface with a circumflex (ˆ) above it.

Throughout this book, we make extensive use of ***phasor representation*** in solving problems involving electromagnetic quantities that vary sinusoidally in time. Letters denoting phasor quantities are printed with a tilde (∼) over the letter.

Table 1-2 **Multiple and submultiple prefixes.**

Prefix	Symbol	Magnitude
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

Thus, $\widetilde{\mathbf{E}}$ is the phasor electric field vector corresponding to the instantaneous electric field vector $\mathbf{E}(t)$. This notation is discussed in more detail in Section 1-7.

Notation Summary

- **Scalar quantity:** medium-weight italic, such as C for capacitance.
- **Units:** medium-weight roman, as in V/m for volts per meter.
- **Vector quantities:** boldface roman, such as $\mathbf{E}$ for electric field vector
- **Unit vectors:** boldface roman with circumflex (ˆ) over the letter, as in $\hat{\mathbf{x}}$.
- **Phasors:** a tilde (∼) over the letter; $\widetilde{E}$ is the phasor counterpart of the sinusoidally time-varying scalar field $E(t)$, and $\widetilde{\mathbf{E}}$ is the phasor counterpart of the sinusoidally time-varying vector field $\mathbf{E}(t)$.

1-3 The Nature of Electromagnetism

Our physical universe is governed by four fundamental forces of nature:

- The ***nuclear force***, which is the strongest of the four, but its range is limited to ***subatomic scales***, such as nuclei.
- The ***electromagnetic force*** exists between all charged

particles. It is the dominant force in ***microscopic*** systems, such as atoms and molecules, and its strength is on the order of 10^{-2} that of the nuclear force.

- The ***weak-interaction force***, whose strength is only 10^{-14} that of the nuclear force. Its primary role is in interactions involving certain radioactive elementary particles.
- The ***gravitational force*** is the weakest of all four forces, having a strength on the order of 10^{-41} of the nuclear force. However, it often is the dominant force in ***macroscopic*** systems, such as the solar system.

This book focuses on the electromagnetic force and its consequences. Even though the electromagnetic force operates at the atomic scale, its effects can be transmitted in the form of electromagnetic waves that can propagate through both free space and material media. The purpose of this section is to provide an overview of the basic ***framework of electromagnetism***, which consists of certain fundamental laws governing the electric and magnetic fields induced by static and moving electric charges, the relations between the electric and magnetic fields, and how these fields interact with matter. As a precursor, however, we will take advantage of our familiarity with gravitational force by describing some of its properties because they provide a useful analogue to those of electromagnetic force.

1-3.1 Gravitational Force: A Useful Analogue

According to Newton's law of gravity, the gravitational force $\mathbf{F}_{g_{21}}$ acting on mass m_2 due to a mass m_1 at a distance R_{12} from m_2 (**Fig. 1-3**) is given by

$$\mathbf{F}_{g_{21}} = -\hat{\mathbf{R}}_{12}\,\frac{Gm_1m_2}{R_{12}^2} \qquad \text{(N)}, \tag{1.2}$$

where G is the universal gravitational constant, $\hat{\mathbf{R}}_{12}$ *is a unit vector that points from m_1 to m_2*, and the unit for force is newton (N). The negative sign in Eq. (1.2) accounts for the fact that the gravitational force is attractive. Conversely, $\mathbf{F}_{g_{12}} = -\mathbf{F}_{g_{21}}$, where $\mathbf{F}_{g_{12}}$ is the force acting on mass m_1 due to the gravitational pull of mass m_2. *Note that the first subscript of $\mathbf{F}_g$ denotes the mass experiencing the force and the second subscript denotes the source of the force.*

▶ The force of gravitation acts at a distance. ◀

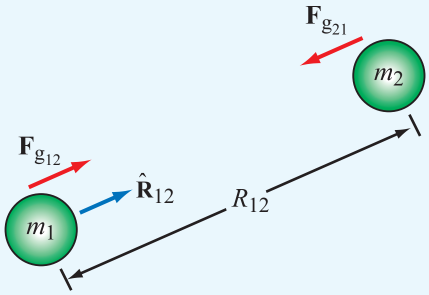


Figure 1-3 Gravitational forces between two masses.

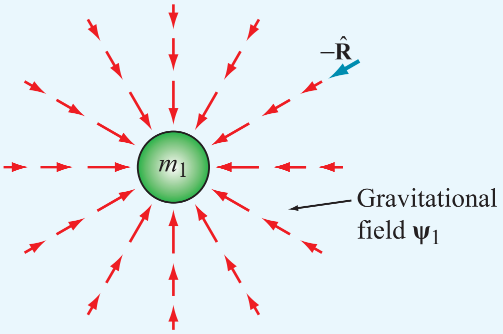


Figure 1-4 Gravitational field $\boldsymbol{\psi}_1$ induced by a mass m_1.

The two objects do not have to be in direct contact for each to experience the pull by the other. This phenomenon of action at a distance has led to the concept of ***fields***. An object of mass m_1 induces a ***gravitational field*** $\boldsymbol{\psi}_1$ (**Fig. 1-4**) that does not physically emanate from the object, yet its influence exists at every point in space such that, if another object of mass m_2 were to exist at a distance R_{12} from the object of mass m_1, the object of mass m_2 would experience a force acting on it equal to

$$\mathbf{F}_{g_{21}} = \boldsymbol{\psi}_1 m_2, \tag{1.3}$$

where

$$\boldsymbol{\psi}_1 = -\hat{\mathbf{R}}\,\frac{Gm_1}{R^2} \qquad \text{(N/kg)}. \tag{1.4}$$

In Eq. (1.4), $\hat{\mathbf{R}}$ is a unit vector that points in the radial direction away from object m_1; therefore, $-\hat{\mathbf{R}}$ points toward m_1. The force due to $\boldsymbol{\psi}_1$ acting on a mass m_2, for example, is obtained from the combination of Eqs. (1.3) and (1.4) with $R = R_{12}$ and $\hat{\mathbf{R}} = \hat{\mathbf{R}}_{12}$. The field concept may be generalized by defining the gravitational field $\boldsymbol{\psi}$ at any point in space such that, when a test mass m is placed at that point, the force $\mathbf{F}_g$ acting on it is related to $\boldsymbol{\psi}$ by

$$\boldsymbol{\psi} = \frac{\mathbf{F}_g}{m}. \tag{1.5}$$

The force $\mathbf{F}_g$ may be due to a single mass or a collection of many masses.

1-3.2 Electric Fields

The electromagnetic force consists of an electrical component $\mathbf{F}_e$ and a magnetic component $\mathbf{F}_m$.

▶ The electrical force $\mathbf{F}_e$ is similar to the gravitational force, but with two major differences:

(1) the source of the electrical field is electric charge, not mass, and

(2) even though both types of fields vary inversely as the square of the distance from their respective sources, electric charges may have positive or negative polarity, resulting in a force that may be attractive or repulsive. ◀

We know from atomic physics that all matter contains a mixture of neutrons, positively charged protons, and negatively charged electrons with the fundamental quantity of charge being that of a single electron, usually denoted by the letter e. The unit by which electric charge is measured is the coulomb (C), named in honor of the eighteenth-century French scientist Charles Augustin de Coulomb (1736–1806). The magnitude of e is

$$e = 1.6 \times 10^{-19} \qquad \text{(C)}. \tag{1.6}$$

The charge of a single electron is $q_e = -e$ and that of a proton is equal in magnitude but opposite in polarity: $q_p = e$.

▶ Coulomb's experiments demonstrated that:

(1) two like charges repel one another, whereas two charges of opposite polarity attract,

(2) the force acts along the line joining the charges, and

(3) its strength is proportional to the product of the magnitudes of the two charges and inversely proportional to the square of the distance between them. ◀

These properties constitute what today is called ***Coulomb's law***, which can be expressed mathematically as

$$\mathbf{F}_{e_{21}} = \hat{\mathbf{R}}_{12}\frac{q_1 q_2}{4\pi\varepsilon_0 R_{12}^2} \qquad \text{(N)} \qquad \textbf{(in free space)}, \tag{1.7}$$

where $\mathbf{F}_{e_{21}}$ is the ***electrical force*** acting on charge q_2 due to charge q_1 when both are in ***free space*** (vacuum), R_{12} is the distance between the two charges, $\hat{\mathbf{R}}_{12}$ *is a unit vector pointing from charge q_1 to charge q_2* (**Fig. 1-5**), and ε_0 is a universal constant called the ***electrical permittivity of free space*** [$\varepsilon_0 = 8.854 \times 10^{-12}$ farad per meter (F/m)]. The two charges are assumed to be isolated from all other charges. The force $\mathbf{F}_{e_{12}}$ acting on charge q_1 due to charge q_2 is equal to force $\mathbf{F}_{e_{21}}$ in magnitude, but opposite in direction: $\mathbf{F}_{e_{12}} = -\mathbf{F}_{e_{21}}$.

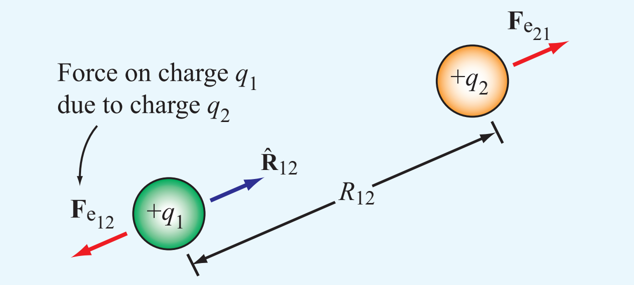


Figure 1-5 Electric forces on two positive point charges in free space.

The expression given by Eq. (1.7) for the electrical force is analogous to that given by Eq. (1.2) for the gravitational force, and we can extend the analogy further by defining the existence of an ***electric field intensity*** $\mathbf{E}$ due to any charge q as

$$\mathbf{E} = \hat{\mathbf{R}}\frac{q}{4\pi\varepsilon_0 R^2} \qquad \text{(V/m)} \qquad \textbf{(in free space)}, \tag{1.8}$$

where R is the distance between the charge and the observation point, and $\hat{\mathbf{R}}$ *is the radial unit vector pointing away from the charge.* **Figure 1-6** depicts the electric field lines due to a positive charge. For reasons that will become apparent in later chapters, the unit for $\mathbf{E}$ is volt per meter (V/m).

▶ If a point charge q' is present in an electric field $\mathbf{E}$ (due to other charges), the point charge will experience a force acting on it equal to $\mathbf{F}_e = q'\mathbf{E}$. ◀

Electric charge exhibits two important properties.

▶ The first property of electric charge is encapsulated by the ***law of conservation of electric charge***, which states that *the (net) electric charge can neither be created nor destroyed*. ◀

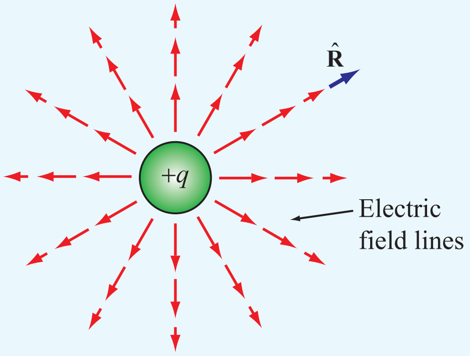


Figure 1-6 Electric field **E** due to charge q.

If a volume contains n_p protons and n_e electrons, then its total charge is

$$q = n_p e - n_e e = (n_p - n_e)e \qquad \text{(C)}. \qquad (1.9)$$

Even if some of the protons were to combine with an equal number of electrons to produce neutrons or other elementary particles, the net charge q remains unchanged. In matter, the quantum mechanical laws governing the behavior of the protons inside the atom's nucleus and the electrons outside it do not allow them to combine.

▶ The second important property of electric charge is embodied by the ***principle of linear superposition***, which states that *the total vector electric field at a point in space due to a system of point charges is equal to the vector sum of the electric fields at that point due to the individual charges*. ◀

This seemingly simple concept allows us in future chapters to compute the electric field due to complex distributions of charge without having to be concerned with the forces acting on each individual charge due to the fields by all of the other charges.

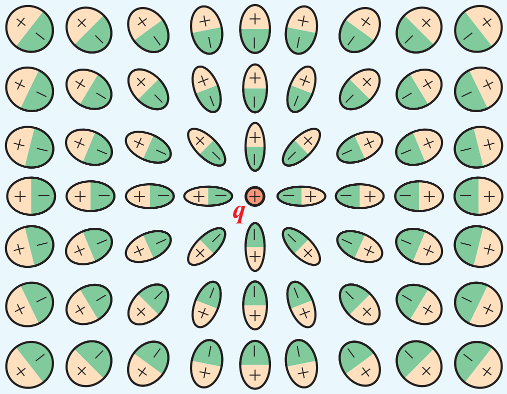


Figure 1-7 Polarization of the atoms of a dielectric material by a positive charge q.

The expression given by Eq. (1.8) describes the field induced by an electric charge residing in free space. Let us now consider what happens when we place a positive point charge in a material composed of atoms. In the absence of the point charge, the material is electrically neutral with each atom having a positively charged nucleus surrounded by a cloud of electrons of equal but opposite polarity. Hence, at any point in the material not occupied by an atom, the electric field **E** is zero. Upon placing a point charge in the material, as shown in **Fig. 1-7**, the atoms experience forces that cause them to become distorted. The center of symmetry of the electron cloud is altered with respect to the nucleus with one pole of the atom becoming positively charged relative to the other pole. Such a polarized atom is called an ***electric dipole***, and the distortion process is called ***polarization***. The degree of polarization depends on the distance between the atom and the isolated point charge, and the orientation of the dipole is such that the axis connecting its two poles is directed toward the point charge, as illustrated schematically in **Fig. 1-7**. The net result of this polarization process is that the electric fields of the dipoles of the atoms (or molecules) tend to counteract the field due to the point charge. Consequently, the electric field at any point in the material is different from the field that would have been induced by the point charge in the absence of the material. To extend Eq. (1.8) from the free-space case to any medium, we replace the permittivity of free space ε_0 with ε, where ε is the permittivity of the material in which the electric field is measured and is therefore characteristic of that particular material. Thus,

$$\mathbf{E} = \hat{\mathbf{R}} \frac{q}{4\pi\varepsilon R^2} \qquad \text{(V/m)}. \qquad (1.10)$$

(material with permittivity ε)

Often, ε is expressed in the form

$$\varepsilon = \varepsilon_r \varepsilon_0 \qquad \text{(F/m)}, \qquad (1.11)$$

where ε_r is a dimensionless quantity called the ***relative permittivity*** or ***dielectric constant*** of the material. For a vacuum, $\varepsilon_r = 1$; for air near the Earth's surface, $\varepsilon_r = 1.0006$; and the values of ε_r for materials that we have occasion to use in this book are tabulated in Appendix B.