Elements of Engineering Electromagnetics

SIXTH EDITION

Nannapaneni Narayana Rao

ILLINOIS ECE SERIES

Elements of Engineering Electromagnetics

Sixth Edition

Elements of Engineering Electromagnetics

Sixth Edition

Nannapaneni Narayana Rao
Edward C. Jordan Professor of Electrical and Computer Engineering
University of Illinois at Urbana–Champaign

Previously published by Pearson Education, Inc.

Library of Congress Cataloging-in-Publication Data on File

About the Cover: Log-periodic dipole antenna array (see page 701) with a view of the William L. Everitt Laboratory of Electrical and Computer Engineering in the background.

There is a Subhashitam (Worthy Saying) in Sanskrit, which says:

Annadaanam param daanam
Vidyadaanam atahparam
Annena kshanikam triptih yaavajjiivamcha vidyayaa.

The gift of food is a great gift
Greater still is the gift of knowledge
While food provides a momentary contentment, knowledge provides a lasting fulfillment.

This "webook (web + book)" constitutes the gift, by the author and his department, of the knowledge of the subject of electromagnetics, based on Maxwell's equations, which "today underpin all modern information and communication technologies."

Om Shri Ganeshaya Namaha

To the land of my birth, India,
the land that gave me the guiding principles of my life:

Matrudevo bhava!	⇒	*Revere the mother as God!*
Pitrudevo bhava!	⇒	*Revere the father as God!*
Acharyadevo bhava!	⇒	*Revere the preceptor as God!*
Atithidevo bhava!	⇒	*Revere the guest as God!*

And to the land of my work, the United States of America,
the land where I pursued the guiding equations of this book:

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt}\int_S \mathbf{B} \cdot d\mathbf{S}$$

$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J} \cdot d\mathbf{S} + \frac{d}{dt}\int_S \mathbf{D} \cdot d\mathbf{S}$$

$$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_V \rho \, dv$$

$$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$$

Contents

Introducing the Illinois ECE Series

The Illinois ECE Series continues a tradition in undergraduate education that has been practiced for more than a century by faculty in the Department of Electrical and Computer Engineering at the University of Illinois. That tradition, which has come to be called "the Illinois Way," balances adherence to the tried-and-true with readiness to change decisively in order to shape a better future.

The Illinois Way encompasses more than textbooks. Early curricula in the department (then called Electrical Engineering) included courses in military drills, drafting, and surveying. Later, Illinois would be the first program in the nation offering a freshman introduction to concepts in circuits, electromagnetics, electronics, control, and digital systems. Computer-based education in the department dates back to 1960 with PLATO (Programmed Logic for Automated Teaching Operations), a time-shared network that gave rise to one of the world's first online communities. Now, students all over the world take ECE courses using Web-based learning environments developed and used by our faculty. The department's greatest pride is its world-class undergraduate instructional laboratories. A century ago, facilities consisted of batteries, electrical machinery, and illumination equipment. Now, the department houses unsurpassed educational laboratories for integrated circuit fabrication, digital signal processing, control systems, computer architecture, and more.

Of course, popular and innovative textbooks have long been a part of the Illinois Way. Former department head and longtime engineering dean at Illinois, William L. Everitt, edited over 100 titles for a series of engineering textbooks published by Prentice Hall in the middle of the last century. Everitt also wrote textbooks. His *Communication Engineering*, first published in 1932 and revised into the 1950s with Illinois colleague G. E. Anner, deserves credit for helping push the electrical engineering profession from its pre-World War II emphasis on power systems to its postwar emphasis on information technology and electronics. Edward C. Jordan, head of the department from 1954 to 1979, wrote *Electromagnetic Waves and Radiating Systems*, long a standard textbook in the field, first published by Prentice Hall in 1950 and revised in 1968. Additionally, M. E. Van Valkenburg, another long-standing faculty member who also

served as head and dean, wrote several influential textbooks, including *Network Analysis*, one of the most internationally popular engineering texts of all time, first published by Prentice Hall in 1955 and revised in 1964 and 1974.

It is fitting, then, that the Illinois ECE Series begins with the sixth edition of N. N. Rao's *Elements of Engineering Electromagnetics*. Professor Rao was hired to join the Illinois faculty in 1965 by Jordan. Prentice Hall published the first edition of *Elements* in 1977; by the time of its fifth edition, dedicated in 2000 to none other than Ed Jordan, the text had established an international reputation for its grounding in time-honored practices even as it evolved progressively from one edition to the next. That is the essence of the Illinois Way.

The Department of Electrical Engineering was established in 1891 when the University of Illinois, one of the first public land-grant institutions chartered after President Abraham Lincoln's signing of the Morrill Land Grant Act, was just 24 years old. Enrollments increased, but steadily, until World War II when the U.S. armed services contracted with the university to train recruits, prompting a boom in the student body. The war also boosted the volume of research contracts handed out by the government, and when Everitt became head in 1944 he took advantage of the new circumstances and led the department to embrace research and teaching in a wide array of electrical engineering-related fields. A computer engineering curriculum was established in the department in 1972, reflecting the department's close involvement with computer work on campus dating back to 1952 with ILLIAC I, one of the first computers built and owned by an educational institution (and which later served as the mainframe for PLATO). In 1984 the department was renamed the Department of Electrical and Computer Engineering.

Today the department enjoys a longstanding, international reputation as one of the premier places in the world for the study of electrical and computer engineering. As of 2003, ECE faculty members advise and instruct more than 1600 undergraduate and over 550 graduate students, while carrying out research funded at a level of $25 million per year. The department is headquartered in the venerable Everitt Laboratory and enjoys world-class, interdisciplinary, Urbana–Champaign campus facilities such as the Beckman Institute for Advanced Science and Technology, the Coordinated Science Laboratory, the Grainger Engineering Library, the Micro and Nanotechnology Laboratory, the National Center for Supercomputing Applications, and the University of Illinois Research Park. Faculty, students, and alumni of the department have established the state of the art in fields ranging from microelectronics to telecommunications, photonics, signal processing, electromagnetics, bioengineering, computer architecture, circuits, and more. A sampling of their achievements follows.

- Professor Josef Tykociner invented a process for making moving pictures with sound. In 1922, he was the first person in the world to demonstrate sound-on-film technology.
- Professor John Bardeen joined the faculty in 1951 after co-inventing the transistor at Bell Labs in 1947. Bardeen would go on to develop the theory of superconductivity at Illinois in 1957. He shared the 1956 Nobel Prize in

physics for the invention of the transistor, and the same prize again in 1972 for the theory of superconductivity. He remained on the ECE staff until his death in 1991.

- Professors Floyd Dunn and William Fry conducted pioneering research in the use of ultrasound as a noninvasive diagnostic and surgical tool as early as the 1950s.
- Alumnus Jack Kilby invented the integrated circuit in 1958 while working for Texas Instruments. Kilby won the 2001 Nobel Prize in physics for his invention.
- Graduate student Dwight Isbell invented the frequency-independent log-periodic antenna in 1959, laying the groundwork for Professor Paul Mayes and graduate student Robert Carrel, who the following year developed the log-periodic resonant-V antenna, which would become the most popular antenna for television reception.
- Professor Y. T. Lo created antenna designs that improved the efficiency of giant radio telescopes, military and civilian radar, airborne and space vehicles, and ground-based communication systems during the Cold War.
- Professors and alumni Donald Bitzer and H. Gene Slottow, along with graduate student Robert Willson, invented the plasma display panel in 1964 as an interface with PLATO workstations. In 2002 they received an Emmy recognizing the importance of their work to the television industry.
- Alumnus Alfred Cho developed molecular beam epitaxy during the 1970s while working at Bell Labs.
- Professor and alumnus Nick Holonyak Jr., who had been Bardeen's first graduate student at Illinois, joined the ECE faculty in 1964 after inventing the first practical light-emitting diode at General Electric. Holonyak and graduate student Ed Rezek demonstrated the first quantum-well laser in 1977. Holonyak, still an active member of the ECE faculty, received the 2003 IEEE Medal of Honor.

The Illinois ECE Series has been conceived with the aim of reintroducing electrical and computer engineering students worldwide to the Illinois Way. Students who appreciate these books are encouraged to visit ECE-Illinois on the web at www.ece.uiuc.edu, or in person at the Everitt Laboratory on the Urbana–Champaign campus.

RICHARD E. BLAHUT
Head, ECE Department, University of Illinois, Urbana–Champaign, IL

JAMES HUTCHINSON
Editor, Publications, ECE Department, University of Illinois, Urbana–Champaign, IL

TOM ROBBINS
Publisher, Pearson Prentice Hall, Pearson Education, Upper Saddle River, NJ

Preface

Electromagnetics textbooks and this edition

Introductory textbooks on engineering electromagnetics can be classified broadly into three categories:

1. One-semester textbooks based on a traditional approach of covering essentially electrostatics and magnetostatics, and culminating in Maxwell's equations and some discussion of their applications.
2. Two-semester textbooks, with the first half or more covering electrostatics and magnetostatics, as in category 1, and the remainder devoted to topics associated with electromagnetic waves.
3. One- or two-semester textbooks that deviate from the traditional approach, with the degree and nature of the deviation dependent on the author.

Most textbooks fall into categories 1 and 2, and only a small minority, including this book, belong to category 3. The deviation from the traditional approach originated with the first edition, a one-semester text in which the basic material was built on time-varying fields and their engineering applications. This enhanced its utility for the one-semester student of engineering electromagnetics, while enabling students who planned to take further (elective) courses in electromagnetics to learn many of the same field concepts and mathematical tools provided by the traditional treatment.

In preparing the second edition, a major revision of the first edition was undertaken by expanding the text for one- or two-semester usage to provide flexibility, while preserving the basic philosophy of the first edition, which arose from the assertion that, as a prerequisite to the first EE course in fields, most schools have an engineering physics course in which the students are exposed to the historical treatment of electricity and magnetism. Subsequent editions have further enhanced the usage by incorporating changes and adding material to satisfy the prerequisite needs pertinent to emerging technologies. For example, the substantial changes leading to the fourth edition were prompted by the increasing need for introductory-level coverage to extend beyond the microwave region and into the optical region of the electromagnetic spectrum, in recognition of the advent of the era of photonics, overlapping with that of electronics.

In the fifth edition, the deviation from the traditional approach was carried further by reorganizing the material and adding topics to associate chapters or parts of chapters with electromagnetic technologies.

An important factor guiding the revisions has been the organization of topics for a first course in electrical engineering, as well as in computer engineering, followed by one or more required or elective courses for electrical engineering students that build on the first course. When the first edition was written for a one-semester course to meet the needs of both groups of students, most of the students were electrical engineering majors, a situation that continued for many years. In recent years, the ratio has changed dramatically, and at present, the numbers for computer engineering majors are comparable to those for electrical engineering majors. Recognizing this development, and to make the intended usage of the book even more explicit than before, I have carried the organization of the topics even further in this edition by dividing the book into two parts.

Part I, entitled "Essential Elements for Electrical and Computer Engineering," is comprised of six chapters:

1. "Vectors and Fields"
2. "Maxwell's Equations in Integral Form"
3. "Maxwell's Equations in Differential Form, and Uniform Plane Waves in Free Space"
4. "Fields and Waves in Material Media"
5. "Electromagnetic Potentials and Topics for Circuits and Systems"
6. "Transmission-Line Essentials for Digital Electronics"

These chapters contain essentially the material in Chapters 1–8 of the fifth edition, except that the organization and treatment of topics is tilted more toward time-varying fields, compared with the fifth edition. Part II, entitled "Essential/Elective Elements" to indicate that they are essential or elective, depending upon the needs of the curriculum, comprises the next five chapters:

7. "Transmission Lines for Communications"
8. "Guided Wave Principles for Electronics and Optoelectronics"
9. "Several Topics for Electronics and Photonics"
10. "Principles of Radiation and Antennas"
11. "Several Solution Techniques"

Chapters 7, 8, 9, and 10 are the same as Chapters 7, 9, 10, and 11, respectively, in the fifth edition, except that I have added the topic of pulses on lossy lines in Chapter 7. Chapter 11, an expanded version of Chapter 12 in the fifth edition, includes the analytical technique of *separation of variables* and the geometrical method of *field mapping*, in addition to the four numerical techniques in that chapter.

Thread of development of material

Some of the salient features of the thread of development of the material, evident from a reading of the table of contents, are the following:

1. Introduce basic concepts of vectors and fields for static as well as time-varying cases at the outset and bring in vector calculus concepts later as needed.
2. Present electric and magnetic field concepts early, and then introduce Maxwell's equations for time-varying fields, first in integral form and then in differential form.
3. Introduce waves and associated concepts by obtaining uniform plane wave solutions from the infinite plane current sheet source, first in free space and then in a material medium.
4. Introduce electromagnetic potentials and cover topics pertinent to devices, circuits, and systems, beginning with *p-n* junction and circuit elements, and progressing through electric- and magnetic-field systems to other topics pertinent to electromechanical systems.
5. Introduce the transmission line concept and develop transmission line time-domain analysis, essential for digital electronics, in a progressive manner, beginning with the case of a resistive load to interconnections between logic gates and culminating in crosstalk on transmission lines.
6. Present sinusoidal steady-state analysis of transmission lines comprising the topics of standing waves, resonance, power transfer, and matching, with emphasis on computer and graphical solutions.
7. Develop principles of guided waves for both electronics and optoelectronics, by confining the treatment to one-dimensional waveguides comprising parallel-plate metallic waveguides and dielectric slab waveguides.
8. Devote a chapter to several topics pertinent to electronics and photonics, including two-dimensional metallic waveguides and optical fibers, pulse broadening due to dispersion, interference and diffraction, and wave propagation in an anisotropic medium.
9. Introduce radiation by obtaining the complete field solution to the Hertzian dipole field through the magnetic vector potential, and then develop the basic concepts of antennas.
10. Devote a chapter to solution techniques, comprising primarily the numerical techniques of the finite-difference method, the method of moments, the finite-element method, and the finite-difference time-domain method, but also including the analytical technique of separation of variables and the geometrical method based on field mapping.

Teaching and learning aids

As in the previous editions, a number of teaching and learning aids are employed: (1) examples distributed throughout the text, (2) practical applications of field concepts and phenomena interspersed among presentations of basic subject matter, (3) descriptions of brief experimental demonstrations suitable for classroom presentation, (4) summary of material and review questions (**Q**) for each chapter, (5) drill problems (**D**) at the end of each section, (6) margin

notes, (7) keywords (**K**) at the end of each section, and (8) review problems (**R**) at the end of each chapter, following the homework problems (**P**). For the book, there are a total of 108 Examples, 158 **D** Problems, 413 **Q** Questions, 422 **P** Problems, and 81 **R** Problems. Answers are provided for 40% of the **P** Problems.

Acknowledgments

I wish to express my appreciation to the more than sixty colleagues at the University of Illinois at Urbana-Champaign who have taught from the previous editions of the book during the 26-year period from 1977 to 2003. Thanks are also due to the numerous users at other schools. The evolution of this book would not have been possible without the many opportunities provided to me by my department heads since I joined the University of Illinois in 1965, beginning with the late E. C. Jordan and followed by G. W. Swenson, Jr., E. W. Ernst, T. N. Trick, S. M. Kang, and R. E. Blahut. Many individuals in the department have provided support over the years. Sheryle Carpenter and Laurie Fisher performed the office duties in an admirable manner, ensuring the smooth functioning of the office at all times during my tenure as Associate Head of the department since 1987. The typing of the manuscript for several editions was done by Kelly Collier in a prompt and skillful manner. It has been a pleasure working with Tom Robbins, my publisher, throughout the endeavor of the inception of the Illinois ECE Series and the production of this book as the first volume in the series. As always, I am deeply indebted to my wife Sarojini for her continued understanding and patience.

N. Narayana Rao
Urbana, Illinois

About the Author

Nannapaneni Narayana Rao was born in Kakumanu, Guntur District, Andhra Pradesh, India. Prior to coming to the United States in 1958, he attended high schools in Pedanandipadu and Nidubrolu; the Presidency College, Madras (now known as Chennai); and the Madras Institute of Technology. He completed high school in Nidubrolu in 1947, and received the B.Sc. degree in physics from the University of Madras in 1952 and the Diploma in electronics from the Madras Institute of Technology in 1955. In the United States, he attended the University of Washington, receiving the M.S. and Ph.D. degrees in electrical engineering in 1960 and 1965, respectively. In 1965, he joined the faculty of the Department of Electrical Engineering, now the Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, Urbana, IL, and has been serving as Associate Head of the Department since 1987.

At the University of Illinois at Urbana–Champaign, Professor Rao carried out research in the general area of ionospheric propagation and authored the undergraduate textbook *Basic Electromagnetics with Applications* (Prentice Hall, 1972), prior to the five previous editions (1977, 1987, 1991, 1994, and 2000) of this book. The fifth edition was translated into Bahasa Indonesia, the language of Indonesia, by a professor of physics at the Bandung Institute of Technology, Bandung. The Salutation to Lord Ganesha (Om Shri Ganeshaya Namaha) in the dedication, which first appeared in the fifth edition, was inspired in part by Professor Rao's visit in January 1999 to the Bandung Institute of Technology, where the image of Ganesha adorns the entrance to the Institute on Jalan Ganesha.

Professor Rao has received numerous awards and honors for his teaching and curricular activities. These include the first Award in Engineering in 1983 from the Telugu Association of North America (TANA), an association of Telugu-speaking people of origin in the State of Andhra Pradesh, India, with the citation, "Dedicated teacher and outstanding contributor to electromagnetics"; a plaque of highest appreciation from the Faculty of Technology, University of Indonesia, Jakarta, Indonesia, for curriculum development in 1985–1986; the Campus Undergraduate Instructional Awards in 1982 and 1988, the Everitt Award for Teaching Excellence from the College of Engineering in 1987, the Campus

Award for Teaching Excellence and the first Oakley Award for Innovation in Instruction in 1989, and the Halliburton Award for Engineering Education Leadership from the College of Engineering in 1991, all at the University of Illinois at Urbana–Champaign; election to Fellow of the IEEE (Institute of Electrical and Electronics Engineers) in 1989 for contributions to electrical engineering education and ionospheric propagation; the AT&T Foundation Award for Excellence in Instruction of Engineering Students from the Illinois–Indiana Section of the ASEE (American Society for Engineering Education) in 1991; the ASEE Centennial Certificate in 1993 for exceptional contribution to the ASEE and the profession of engineering; the IEEE Technical Field Award in Undergraduate Teaching in 1994 with the citation, "For inspirational teaching of undergraduate students and the development of innovative instructional materials for teaching courses in electromagnetics"; and the Excellence in Education Award from TANA in 1999.

In Fall 2003, Professor Rao was named to be the first recipient of the Edward C. Jordan Professorship in Electrical and Computer Engineering, created to honor the memory of Professor Jordan, who served as Department Head for 25 years, and to be held by a "member of the faculty of the department who has demonstrated the qualities of Professor Jordan and whose work would best honor the legacy of Professor Jordan."

A Tribute to Edward C. Jordan

Just as one's personal life is influenced by others, most notably parents, one's professional life can be influenced by certain individuals. In some cases, the influence can be profound. Edward C. Jordan has had such profound influence on my long professional career at Illinois.

Edward C. Jordan was born in Edmonton, Alberta, Canada, on December 31, 1910. He received the B.S. degree in 1934 and the M.S. degree in 1936 from the University of Alberta, and the Ph.D. degree from The Ohio State University in 1940. Upon completing his doctoral degree, he served for one year as instructor at Worcester Polytechnic Institute. He returned to Ohio State University in 1941, where he was on the faculty until 1945. In 1945, he followed his mentor, William L. Everitt, to the University of Illinois. At the University of Illinois, Dr. Jordan served as associate professor from 1945 to 1947, and professor from 1947 to 1979. In 1954, he was named Head of the Department of Electrical Engineering, in which capacity he served for 25 years until his retirement in 1979. Edward C. Jordan passed away on October 18, 1991.

Professor Jordan's legendary contributions were in electrical engineering education and educational administration. His popular textbook, *Electromagnetic Waves and Radiating Systems*, was first published by Prentice Hall in 1950. A second edition, co-authored with K.G. Balmain, was published in 1968. He received many honors in his career, notable among them being the prestigious IEEE Education Medal. He was regarded as the most revered department head, for his commitment to building a broad-based department of national repute and for his skillful administration.

I am deeply grateful for Professor Jordan's influence on my professional career, and I am immensely honored by my connection to him: To have studied from his classic 1950 textbook while a student in India in the 1950's; to have been a member of the faculty and the administration of the department built by this noble individual; to have authored textbooks on the same subject as that of his famous book; to be the first holder of the professorship named after this "father" of the department; and to pay tribute to this individual of "electromagnetic" personality in this book on electromagnetics, the lead volume in the new Illinois ECE Series.

N. Narayana Rao
Urbana, Illinois

Elements of Engineering Electromagnetics

Sixth Edition