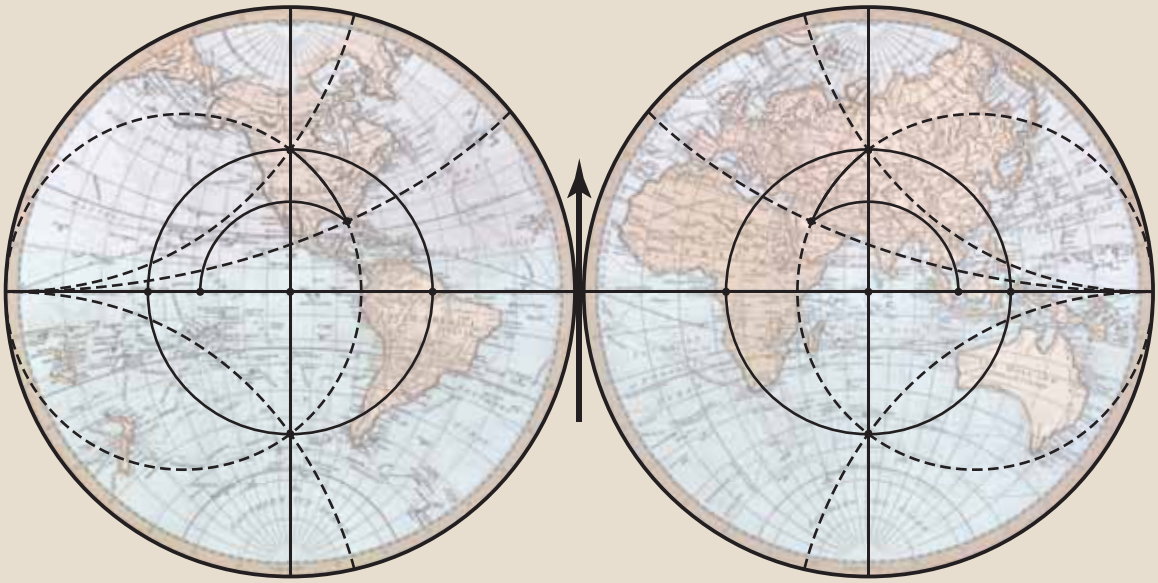
Fundamentals of Electromagnetics for Electrical and Computer Engineering

Nannapaneni Narayana Rao



ILLINOIS ECE SERIES

Fundamentals of Electromagnetics for Electrical and Computer Engineering

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About the Front Cover Image: Figure 7.14 (right), application of Smith Chart in transmission-line analysis, and its mirror image (left), inside the circles of Figure 9.5(c), the field intensity radiation pattern of the Hertzian dipole antenna, superimposed on a historic depiction of the two hemispheres of the globe, reflecting the spirit of the dedication.

Pearson Education, Inc. has transferred the rights of this 2009 edition to the author in December 2017. The author has decided to make the book available on the web free of charge to the teachers, students, and others all over the world for the purpose of teaching and learning the fundamentals of electromagnetics. Any use involving monetary transaction violates the spirit of this decision.

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."

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"Fill your heart with love
and express it in everything you do."
—Amma Mata Amritanandamayi Devi,
Chancellor, Amrita Vishwa Vidyapeetham

To students all over the world,
I offer to you this book on Electromagnetics,
the "Mother of Electrical and Computer Engineering,"
with the spirit of the above message from Amma,
the "Mother of Compassion!"

Contents

Preface

". . . I am talking about the areas of science and learning that have been at the heart of what we know and what we do, that which has supported and guided us and which is fundamental to our thinking. It is electromagnetism in all its many forms that has been so basic, that haunts us and guides us. . . ."

—Nick Holonyak, Jr., the John Bardeen Endowed Chair Professor of Electrical and Computer Engineering and Physics at the University of Illinois at Urbana–Champaign, and the inventor of the semiconductor visible LED, laser, and quantum-well laser

"The electromagnetic theory, as we know it, is surely one of the supreme accomplishments of the human intellect, reason enough to study it. But its usefulness in science and engineering makes it an indispensable tool in virtually any area of technology or physical research."

—George W. Swenson, Jr., Professor Emeritus of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign

The above quotes from two of my distinguished colleagues at the University of Illinois underscore the fact that electromagnetics is all around us. In simple terms, every time we turn on a switch for electrical power or for electronic equipment, every time we press a key on our computer keyboard or on our cell phone, or every time we perform a similar action involving an everyday electrical device, electromagnetics comes into play. It is the foundation for the technologies of electrical and computer engineering, spanning the entire electromagnetic spectrum, from d.c. to light. As such, in the context of engineering education, it is fundamental to the study of electrical and computer engineering. While the fundamentals of electromagnetic fields remain the same, the manner in which they are taught may change with the passing of time owing to the requirements of the curricula and shifting emphasis of treatment of the fundamental concepts with the evolution of the technologies of electrical and computer engineering.

Three decades ago, I wrote a one-semester textbook, the first edition of *Elements of Engineering Electromagnetics*, dictated solely by the reduction in the curricular requirement in electromagnetics at the University of Illinois from a three-semester required sequence to a one-semester course, owing to the pressure of increasing areas of interest and fewer required courses. The approach used for the one-semester book was to deviate from the historical treatment and base it upon dynamic fields and their engineering applications, in view of the student's earlier exposure in engineering physics to

the traditional approach of static fields and culminating in Maxwell's equations. Less than ten years after that, a relaxation of the curricular requirements coupled with the advent of the PC resulted in an expanded second edition of the book for two-semester usage. Subsequent editions have essentially followed the second edition.

Interestingly, the approach that broke with the tradition with the first edition has become increasingly relevant from a different context, because with the evolution of the technologies of electrical and computer engineering over time, the understanding of the fundamental concepts in electromagnetics based on dynamic fields has become increasingly important. Another feature of the first edition of *Elements of Engineering Electromagnetics* was the treatment of the bulk of the material through the use of the Cartesian coordinate system. This was relaxed in the subsequent editions, primarily because of the availability of space for including examples involving the geometries of cylindrical and spherical coordinate systems, although the inclusion of these examples is not essential to the understanding of the fundamental concepts.

This book, which is a one-semester textbook, combines the features of the first edition of *Elements of Engineering Electromagnetics* with the treatment of the fundamental concepts in keeping with the evolution of technologies of electrical and computer engineering. Specifically, the approach of beginning with Maxwell's equations to introduce the fundamental concepts is combined with the treatment of the different categories of fields as solutions to Maxwell's equations and using the thread of statics-quasistatics-waves to bring out the frequency behavior of physical structures. Thus, some of the salient features of the first nine chapters of the book consist of the following:

1. Using the Cartesian coordinate system for the bulk of the material to keep the geometry simple and yet sufficient to learn the physical concepts and mathematical tools, while employing other coordinate systems where necessary
2. Introducing Maxwell's equations for time-varying fields first in integral form and then in differential form early in the book
3. Introducing uniform plane wave propagation by obtaining the field solution to the infinite plane current sheet of uniform sinusoidally time-varying density
4. Introducing material media by considering their interaction with uniform plane wave fields
5. Using the thread of statics-quasistatics-waves to bring out the frequency behavior of physical structures, leading to the development of the transmission line and the distributed circuit concept
6. Covering the essentials of transmission-line analysis both in frequency domain and time domain in one chapter
7. Introducing metallic waveguides by considering the superposition of obliquely propagating uniform plane waves and dielectric waveguides following the discussion of reflection and refraction of plane waves
8. Obtaining the complete solution to the Hertzian dipole fields through a successive extension of the quasistatic field solution so as to satisfy simultaneously the two Maxwell's equations, and then developing the basic concepts of antennas

The final chapter is devoted to six supplementary topics, each based on one or more of the previous six chapters. It is intended that the instructor will choose one or more of these topics for discussion following the corresponding previous chapter(s). Material on cylindrical and spherical coordinate systems is presented in appendices so that it can be studied either immediately following the discussion of the corresponding material on the Cartesian coordinate system or only when necessary.

From considerations of varying degrees of background preparation at different schools, a greater amount of material than can be covered in an average class of three semester-hour credits is included in the book. Worked-out examples are distributed throughout the text, and in some cases, extend the various concepts. Summary of the material and a number of review questions are included for each chapter to facilitate review of the chapters.

I wish to express my gratitude to the numerous colleagues at the University of Illinois at Urbana–Champaign (UIUC) who have taught from my books over a period of 35 years, beginning with my first book in 1972, and to the numerous users of my books worldwide. Technological advances in which electromagnetics continues to play a major role have brought changes in this span of time beginning with the introduction of the computer engineering curriculum in my department at UIUC in 1972, followed by the name change of the department from electrical engineering to electrical and computer engineering in 1984, to transforming the way of life in the present-day world from "local" to "global."

The title of this book is a recognition of the continuing importance of a core course in electromagnetics in both electrical engineering and computer engineering curricula, in this high-speed era. My joint affiliation with UIUC, my "home" institution in the United States in the West, and Amrita Vishwa Vidyapeetham in my "homeland" of India in the East is a gratifying happening owing to the state of the world that, with the transformation from "local" to "global," East is no longer just East, and West is no longer just West, and the twain have met!

N. Narayana Rao

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, Chromepet. 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, at the University of Illinois at Urbana–Champaign (UIUC), Urbana, Illinois, and served on the faculty of that department until 2007.

Professor Rao retired from UIUC in 2007 as Edward C. Jordan Professor of Electrical and Computer Engineering, to which he was named to be the first recipient in 2003. The professorship was 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." During the 42 tears of tenure at the University of Illinois, Professor Rao was engaged in research, teaching, administration, and international activities.

Professor Rao's research focused on ionospheric propagation. In his teaching, he taught a wide variety of courses in electrical engineering. He developed courses in electromagnetic fields and wave propagation, and has published undergraduate textbooks: *Basic Electromagnetics with Applications* (Prentice-Hall, 1972), six editions of *Elements of Engineering Electromagnetics* (Prentice-Hall, 1977, 1987, 1991, 1994, 2000, and 2004), and a special Indian Edition of the sixth edition of *Elements of Engineering Electromagnetics* (Pearson Education, 2006). In administration, he served as Associate Head of the Department for Instructional and Graduate Affairs for 19 years, from 1987 to 2006.

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. He is a Life Fellow of the IEEE and a Life Member of the ASEE.

Professor Rao has been active internationally in engineering education. He was involved in institutional development at the University of Indonesia in Jakarta during 1985–1986. In summer 2006, he offered the first course on the EDUSAT satellite network from the Amrita Vishwa Vidyapeetham (Amrita University) in Ettimadai, Coimbatore, Tamil Nadu, India, under the Indo-U.S. Interuniversity Collaborative Initiative in Higher Education and Research. In October 2006, Amrita University named Professor Rao as its first Distinguished Amrita Professor.

Professor Rao will be continuing his academic activities, as Edward C. Jordan Professor Emeritus of Electrical and Computer Engineering at the University of Illinois and Distinguished Amrita Professor of Engineering at Amrita University.

Gratitude and "Grattitude"

I came to the United States 50 years ago in 1958 with $50, a passport from my motherland, India, and undergraduate education in my then-technical field of electronics from the Madras Institute of Technology in India. I received my Ph.D. in electrical engineering from the University of Washington and joined what is now the Department of Electrical and Computer Engineering (ECE) at the University of Illinois at Urbana–Champaign (UIUC) in 1965, attracted by the then-department head, Edward C. Jordan, who brought the department to national and international fame as its head for 25 years from 1954 to 1979. After 42 years of tenure in this department, I retired, effective June 1, 2007, as the Edward C. Jordan Professor Emeritus of Electrical and Computer Engineering.

In recent years, I have been engaged in engineering education in India. In December 2005, I got connected to the "Hugging Saint," and "Mother of Compassion," the humanitarian and spiritual leader Amma Mata Amritanandamayi Devi, Chancellor of Amrita Vishwa Vidyapeetham (Amrita University), popularly known as "Amma," meaning "Mother," all over the world. Since then, I have been involved with Amrita University, where I now have the position of Distinguished Amrita Professor of Engineering, offered to me in October 2006. My involvement with Amrita began in a special way, as the first faculty member from the United States teaching from the Amrita campus in Ettimadai, Coimbatore, Tamil Nadu, to students at remote locations on the interactive satellite E-learning Network, under the Indo-U.S. Inter-University Collaborative Initiative in Higher Education and Research, in summer 2006.

I am grateful to many individuals, beginning with my late parents, and for many things. I came with the solid foundation laid at my alma mater in India and acquired more education at my alma mater in the United States and prospered in my profession at Illinois. For all of this, I am grateful to my two Lands, the land of my birth, India, for the foundation, and the land of my work, America, for the prosperity. I am grateful to Amma Mata Amritanandamayi Devi for attracting me to Amrita University, thereby giving me the opportunity for "serving the needs of students of various parts of the world," in the words of former President of India, Bharat Ratna, Dr. A. P. J. Abdul Kalam, with this book, bearing my joint affiliation with Illinois and Amrita.

In the words of the late Gurudeva Sivaya Subramuniyaswami of the Kauai Aadheenam, Kauai, Hawaii: "Gratitude and appreciation are the key virtues for a

better life. They are the spell that is cast to dissolve hatred, hurt and sadness, the medicine which heals the subjective states of mind, restoring self-respect, confidence, and security." I am grateful that I am the author of this book and its predecessor books, over the span of more than 35 years, for introducing electromagnetic theory, commonly known as electromagnetics (EM), to students all over the world. Here, I would like to reconstruct the trail of this gratitude beginning in the 1950s.

One day during the academic year 1957–1958, I had the pleasure of having afternoon refreshments with William L. Everitt in the dining hall of the Madras Institute of Technology (MIT), Chromepet, along with some others in the electronics faculty of MIT. William L. Everitt was then the dean of the College of Engineering at the University of Illinois, Urbana, as it was then known. Dean Everitt was visiting India because the University of Illinois was assisting with the development of IIT (Indian Institute of Technology), Kharagpur, the first of the IITs. Dean Everitt came to Madras (presently Chennai) at the invitation of William Ryland Hill, who was the visiting head of the electronics faculty of MIT during that one year, on leave from the University of Washington in Seattle, Washington.

I happened to be on the staff of the electronics faculty then, having completed my diploma in electronics after three years of study during 1952–1955 and six months of practical training, following my B.Sc. (Physics) from the University of Madras, having attended the Presidency College. One of the subjects I studied at MIT was electromagnetic theory, from the book *Electromagnetic Waves and Radiating Systems*, by Edward C. Jordan, who was then the head of the Department of Electrical Engineering at the University of Illinois. I can only say that my learning of electromagnetic theory at that time was hazy at best, no reflection on Jordan's book.

While I was a student at MIT, one of our great lecturers, by the name of S. D. Mani, was leaving to take a new job in Delhi, for which we gave him a send-off party. After the send-off party, we all went to the Chromepet Railway Station adjacent to the Institute to bid a final goodbye to him on the platform. While on the platform waiting for the electric train to arrive from the neighboring station, Tambaram, he specifically called to me and said, "Narayana Rao, someday you will become the president of a company!"

Contrary to what S. D. Mani said, with his great characteristic style, I did not go on to even work in a company. Instead, William Ryland Hill "took" me to the EE Department at the University of Washington in 1958, then chaired by Austin V. Eastman, a contemporary of Edward Jordan. There, I pursued my graduate study in electrical engineering and received my Ph.D. in 1965, with Howard Myron Swarm as my advisor, in the area of ionospheric physics and propagation, and taking courses from Akira Ishimaru, among others. Eastman gave me the opportunity of teaching courses just like a faculty member, as an instructor, because of my teaching experience at MIT, and the good word of Ryland Hill. That was when I fell in love with the teaching of "transmission lines," from the electromagnetics aspect, which then extended beyond transmission lines and later led to the writing of my books.

Never did I envision during those years that in 1965, after completing my Ph.D. at the University of Washington, I would become a faculty member and be writing my

books in the Jordan-built Department of Electrical and Computer Engineering (as it is now called) in the Everitt-built College of Engineering at the University of Illinois at Urbana-Champaign, as it is now known. Never did I envision that I would spend my entire professional career since 1965 in the hallowed halls of the William L. Everitt Laboratory of Electrical and Computer Engineering, which I call the "Temple of Electrical and Computer Engineering," along with personalities such as distinguished colleagues Nick Holonyak, Jr., and George W. Swenson, Jr. Never did I envision that not only would I be writing books for teaching electromagnetics, following the tradition of Jordan, but also would be holding a professorship, and now an emeritus professorship, bearing his name.

I believe that gratitude is something you can neither express adequately in words nor demonstrate adequately in deeds. Nevertheless, I have tried on certain occasions to express it in words, and demonstrate it in deeds, which I would like to share with you here:

To my alma mater, the Madras Institute of Technology, on the occasion of the Institute Day on February 26, 2004, in the presence of the then-Governor of Tamil Nadu, Sri P. S. Ramamohan Rao, a classmate of mine while in Presidency College, for presenting the sixth edition of my book, *Elements of Engineering Electromagnetics:*

So, Madras Institute of Technology, my dear alma mater
Where I went to school fifty years ago this year
Today I present to you this historic volume
The product of the work of my lifetime
For which fifty years ago you laid the foundation
That I cherished all these years with much appreciation
Please accept this book as a token of my utmost gratitude
Which I offer to you in the spirit of "Revere the preceptor as God"
Hopefully I will be back with Edition No. 7
To express my gratitude to you again in 2007!

And I did go back to my alma mater in January 2007, not to present Edition No. 7, but rather a special Indian Edition of Edition No. 6, which could be considered as Edition No. 7!

At the conclusion of the response speech on the occasion of my investiture as the Edward C. Jordan Professor of Electrical and Computer Engineering, on April 14, 2004:

To Edward C. Jordan, the "father" of my department
Fifty years ago, I may have studied EM from your book with much bewilderment
But today, I offer to you this book on EM which I wrote with much excitement
In appreciation of your profound influence on my professional advancement.

To my alma mater, the EE Department at the University of Washington, giving the keynote speech and presenting the sixth edition of *Elements of Engineering*

Electromagnetics, at the kick-off event for the Centennial Celebration of the Department on April 28, 2006:

> *To the EE Department at the University of Washington*
> *From this grateful alumnus who received from you his graduate education*
> *Not just graduate education but seven years of solid academic foundation*
> *For my successful career at the University of Illinois at Urbana–Champaign*
> *During which I have written six editions of this book on electromagnetics*
> *Besides engaging in the variety of all the other academic activities*
> *I present to you this book with utmost appreciation*
> *On the occasion of your centennial celebration!*

And when you are grateful in life, things continue to happen to you to allow you to be even more grateful. Even as late as November 2005, I did not envision that I would become connected to Amrita University of Amma Mata Amritanandamayi Devi. The opportunity came about as a consequence of the signing of a memorandum of understanding (MOU) in December 2005 between a number of U.S. Universities, including UIUC and the University of Washington, and Amrita University in partnership with the Indian Space Research Organization (ISRO) and the Department of Science and Technology of the Government of India. The MOU had to do with an initiative, known as the Indo-U.S. Inter-University Collaborative Initiative in Higher Education and Research, and allowed for faculty from the United States to offer courses for e-learning on the ISRO's EDUSAT Satellite Network and to pursue collaborative research with India. The Initiative was launched by the then President of India, Bharat Ratna, A. P. J. Abdul Kalam, from New Delhi on the EDUSAT Satellite Network on December 8, 2005.

A delegation from the United States went to India on this occasion, and following the launching ceremony at Ettimadai, Coimbatore, Tamil Nadu, where the main Amrita campus is located, the delegation went to Amritapuri in the state of Kerala to meet with Amma on December 9. That was when I got connected to Amma, and things began to happen. Within the next year, I became the first professor to offer a course on the EDUSAT Satellite Network—a 5-week course in summer 2006, entitled "Electromagnetics for Electrical and Computer Engineering," in memory of Edward C. Jordan, using as the textbook a special Indian Edition of *Elements of Engineering Electromagnetics, Sixth Edition*, published in this connection by Pearson Education and containing a message by former President Abdul Kalam, forewords by UIUC Chancellor Richard Herman, UIUC Provost Linda Katehi, and ECE Professor Nick Holonyak, Jr., and an introductory chapter called "Why Study Electromagnetics?" offering 18 very thoughtful responses to that question, most of them provided by UIUC ECE faculty members.

So, I did not become the "president" of a company, as S. D. Mani proclaimed on the platform of the Chromepet Railway Station. Instead, I went on to become a "resident" of the William L. Everitt Laboratory of Electrical and Computer Engineering, the "Temple of Electrical and Computer Engineering,"—the crown jewel of the campus that provided education to numerous presidents of companies—located at the northeast corner of the intersection of Wright and Green Streets in Urbana, Illinois, on the Campus of the University of Illinois at Urbana–Champaign!

And from the "Temple of Electrical and Computer Engineering" in Urbana, shown above, my gratitude took me to my motherland, halfway around the world, as an "IndiAmerican," a word that I coined implying that the "Indian" and the "American" are inseparable, and which inspired former President Abdul Kalam. There, I reached the destination in my journey at Amma Mata Amritanandamayi Devi's Amrita Vishwa Vidyapeetham, where I got connected to the "young minds" of my motherland, shown in the picture below, along with some staff and my wife and our daughter, taken on August 11, 2006, the last day of the class in front of the beautiful main building of the campus.

I have read somewhere that destination is a journey and not a success in itself. And therefore, the journey began at Amrita and is continuing! As though for this purpose and owing to a combination of circumstances, I became the first Distinguished Amrita Professor of Engineering in October 2006, at which time I decided to write this book, and hence began working on it while at Amrita in Ettimadai. Subsequently, I retired from UIUC effective June 1, 2007, becoming the Edward C. Jordan Professor Emeritus of Electrical and Computer Engineering, so that my journey is now continuing as Jordan Professor Emeritus from Illinois and Distinguished Amrita Professor from Amrita, wherever I am in this global world.

I always believed in the power of education—transcending the boundaries of national origin, race, and religion—to assure the future of the world. Throughout my life, I have been involved in education, as a student, professor, researcher, teacher, author, and administrator. The sheer enjoyment of my work led me to coining the word "grattitude," in 2005, in answer to people wondering if I would ever retire from my job at Illinois. "Grattitude" is a word combining "gratitude" and "attitude," and meaning an "attitude of gratitude." In my journey, I feel grattitude for the opportunity I have been given to help facilitate the education of the wonderful youth from countries all over the world, through my books, teaching, and international activities. I have learned that engaging in an activity with "grattitude" yields immediate enjoyment. I conclude this story of "gratitude and grattitude" with the following poem:

To the students from all around the world
And to the students all over the world
EMpowered by the Jordan name
And inspired by the Amrita name
I offer to you this book on EM
Beginning with this poem which I call PoEM
If you are wondering why you should study EM
Let me tell you about it by means of this PoEM
First you should know that the beauty of EM
Lies in the nature of its compact formalism
Through a set of four wonderful EMantras
Familiarly known as Maxwell's equations
They might be like mere four lines of mathematics to you
But in them lie a wealth of phenomena that surround you
Based on them are numerous devices
That provide you everyday services
Without the principles of Maxwell's equations
Surely we would all have been in the dark ages
Because there would be no such thing as electrical power
Nor would there be electronic communication or computer
Which are typical of the important applications of ECE
And so you see, EM is fundamental to the study of ECE.

So, you are curious about learning EM
Let us proceed further with this PoEM
First you should know that **E** *means electric field*
And furthermore that **B** *stands for magnetic field*
Now, the static **E** *and* **B** *fields may be independent*

But the dynamic **E** *and* **B** *fields are interdependent*
Causing them to be simultaneous
And to coexist in any given space
Which makes EM very illuminating
And modern day life most interesting
For it is the interdependence of **E** *and* **B** *fields*
That is responsible for electromagnetic waves
In your beginning courses you might have learnt circuit theory
It is all an approximation of electromagnetic field theory
So you see they put the cart before the horse
But it is okay to do that and still make sense
Because at low frequencies circuit approximations are fine
But at high frequencies electromagnetic effects are prime
So, whether you are an electrical engineer
Or you happen to be a computer engineer
Whether you are interested in high frequency electronics
Or maybe high-speed computer communication networks
You see, electromagnetic effects are prime
Studying the fundamentals of EM is sublime.

If you still have a ProblEM with EM,
Because it is full of abstract mathematics,
I say, my dear ECE student who dislikes electromagnetics
Because you complain it is full of abstract mathematics
I want you to know that it is the power of mathematics
That enabled Maxwell's prediction through his equations
Of the physical phenomenon of electromagnetic radiation
Even before its finding by Hertz through experimentation
In fact it was this accomplishment
That partly resulted in the entitlement
For the equations to be known after Maxwell
Whereas in reality they are not his laws after all
For example the first one among the four of them
Is Faraday's Law expressed in mathematical form
You see, mathematics is a compact means
For representing the underlying physics
Therefore do not despair when you see mathematical derivations
Throughout your textbook on the Fundamentals of Electromagnetics
Instead look through the derivations to understand the concepts
Realizing that mathematics is only a means to extend the physics
Think of yourself as riding the horse of mathematics
To conquer the new frontier of electromagnetics
Let you and me together go on the ride
As I take you through the steps in stride, with grattitude!

N. Narayana Rao