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Fundamentals of Electromagnetics for Engineering

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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

Preface to the Indian Edition

FROM AN INDIAMERICAN WITH GRATITUDE AND GRATTITUDE

Here is a little poem for Mother
My mother, your mother, our mother
The mother of a billion people on her land
The mother of millions of people outside her land
Mother India, my citizenship is American
But the blood you sent me with is Indian
So, as they say, am I an Indian American?
Or, am I an American of Indian origin?
I may be known as an Indian American
Or they may call me an American of Indian origin
But mother, I feel more like an IndiAmerican!
With the "Indian" fused into "American"
And I shall always be an IndiAmerican!
As my "Indian" is inseparable from my "American"
Or, for that matter, from any other "an!"

The above poem, which I call the "IndiAmerican Poem," is a slightly modified version of a poem I composed for the Republic Day in January 2006 and sent to the then-President, Bharat Ratna, Dr A. P. J. Abdul Kalam. Dr Kalam was kind enough to send me a brief letter, stating: *Dear Prof. Rao, I was going through the poem composed by you, "Mother, I am an IndiAmerican!" It is indeed very inspiring. My best wishes to you. Yours Sincerely, A. P. J. Abdul Kalam*. The IndiAmerican Poem appeared in the Preface of the Indian Edition of "Elements of Engineering Electromagnetics, Sixth Edition," published by Pearson Education in July 2006, and "dedicated to 'the young minds that will take this country to the greatest heights,' in the words of the President of India, Bharat Ratna, Dr A. P. J. Abdul Kalam, a fellow alumnus of the Madras Institute of Technology."

As stated in the section on "Gratitude and Grattitude," in which the word, "grattitude," is explained, I always believed in the power of education—transcending the boundaries of national origin, race, and religion—to assure the future of the world. When I left India for the United States of America in 1958, there were only a few technological institutions in a given state in India. I came with the solid foundation laid at my alma mater, the Madras Institute of Technology (MIT), which to me is not just the MIT, the "Madras Institute of Technology" but the MIT, the "Mother Institute of Technology." I acquired more education at my alma mater in the United States of America, the University of Washington (UW), and prospered in my profession of engineering education at the University of Illinois at Urbana-Champaign (UIUC). 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 would now like to share with you a fascinating and heart-warming story because it has a bearing with my belief in the power of education, before proceeding on to items of direct relevance to the subject matter of this book.

AMERICA, CHINA, AND INDIA

On April 18, 2006, while I was staying in the Le Meridien Hotel in New Delhi on one of my trips to the motherland, along with my wife, I received an email from one of my former colleagues at UIUC and an emeritus faculty member, on some department business. Along with it, he forwarded an e-mail from Da Hsuan Feng, then Vice President for Research and Economic Development and Professor of Physics at the University of Texas at Dallas, and now Senior Executive Vice President at National Chung Kung University in Tainan, Taiwan. Da Hsuan Feng was born in New Delhi in 1945 to Chinese parents, when his father, Paul Kuo-Jin Feng, was stationed as a foreign correspondent.

Paul Kuo-Jin Feng died tragically when Da Hsuan Feng was a young boy so that he knew little about what his father did, according to him. On the afternoon of April 18, 2006, it suddenly occurred to him that it might be interesting to google "Paul Feng." And he did just that and the results absolutely astounded him! It returned two websites, both of which were the same. What came to him on his screen stunned him so much that for a moment he was almost paralyzed! From an article, "Forging an Asian identity," by Manoj Das in The Hindu of January 7, 2001, he read the following: Speaking to Mr. Paul Feng of the Central News Agency on January 20, 1946, Pundit Jawaharlal Nehru, the first Prime Minister of India, said, "If China and India hold together, the future of Asia is assured." This holding together need not be confined to diplomacy; it can, by all means, be a psychological force that can work wonders in the realms of creativity...

Da Hsuan Feng was stunned that 60 years ago then, his father was THE person who heard the profound statement—"If China and India hold together, the future of Asia is assured"—from Pundit Nehru. I was in high school in 1946, and from 1947, when I joined college in Madras, until I left India for the United States, I had several occasions to see the revered Prime Minister. Since I received the e-mail when I was in India in New Delhi in a hotel in a room overlooking the Parliament building and the Presidential mansion, where I met President Kalam three times in the preceding five months, the statement felt even more profound to me.

As I responded to my colleague with a copy to Da Hsuan Feng on April 20, 2006, just before my departure back to the United States after a very successful trip, from New Delhi: "Now, 60 years after that, that statement is even more significant. I would go further and say, with utmost reverence to Pundit Nehru, that today, if America, China, and India hold together, the future of the world is assured. In no other sphere of endeavor is the 'holding together' more important than in the sphere of education, because that is where future leaders are cultivated. It is in this regard that UIUC comes into the picture. And the reason I am here in India is on the matter of developing relations in India...."

It is my hope that this book and its original U.S. edition and its international versions serve as a contribution, however small, in this regard by propagating the knowledge on the fundamentals of electromagnetics to students and academics throughout the world, transcending the boundaries of national origin, race, and religion.

INDIAN EDITION VERSUS THE U.S. EDITION

Differences in Terminology

This Indian edition bears the title, *Fundamentals of Electromagnetics for Engineering*, whereas the original U.S. edition is entitled, *Fundamentals of Electromagnetics for Electrical and Computer Engineering*, reflecting the differences in terminology associated with the use of the term, "electrical," in the Indian and American systems of engineering education. As is commonly known, in engineering education in the United States of America, the term "electrical" refers to the totality of what are known in India by the terms, "electrical," "electronics," and "communications." In Indian engineering education, following the British system, the use of "electrical" is generally confined to the areas of power and energy systems and control. Because this book serves the needs of all three of the engineering disciplines, "electrical," "electronics," and "communications," as well as the "computer engineering" discipline, in the Indian system, it is titled, *Fundamentals of Electromagnetics for Engineering*.

The Terminology, "Electrical and Computer Engineering"

Because the term "electrical and computer engineering" is used in the rest of the front matter of this book, it is of interest to elaborate upon this terminology. In engineering departments in the United States educational institutions, electrical and computer engineering is generally one academic department, although not in all institutions. The name, ECEDHA, Electrical and Computer Engineering Department Heads Association, reflects this situation. In the College of Engineering at the University of Illinois at UIUC, the Department of Electrical and Computer Engineering (ECE) offers two undergraduate programs leading to the Bachelor of Science degrees: Electrical Engineering and Computer Engineering. The following two paragraphs, taken from the descriptions of these two undergraduate programs, provide an understanding of the scope of these disciplines.

Scope of the Fields of Electrical Engineering and Computer Engineering

"A list of the twenty greatest engineering achievements of the twentieth century compiled by the National Academy of Engineering includes ten achievements primarily related to the field of *electrical engineering*: electrification, electronics, radio and television, computers, telephone, Internet, imaging, household appliances, health technologies, and laser and fiber optics. The remaining achievements in the list—automobile, airplane, water supply and distribution, agricultural mechanization, air conditioning and refrigeration, highways, spacecraft, petroleum/petrochemical technologies, nuclear technologies, and high-performance materials—also require knowledge of electrical engineering to differing degrees. In the twenty-first century, the discipline of electrical engineering continues to be one of the primary drivers of change and progress in technology and standards of living around the globe."

"*Computer engineering* is a discipline that applies principles of physics and mathematics to the design, implementation, and analysis of computer and communication systems. The discipline is broad, spanning topics as diverse as radio communications, coding and encryption, computer architecture, testing and analysis of computer and communication systems, vision, and robotics. A defining characteristic of the discipline is its grounding in physical aspects of computer and communication systems. Computer engineering concerns itself with development of devices that exploit physical phenomena to store and process information, with the design of hardware that incorporates such devices, and with software that takes advantage of this hardware's characteristics. It addresses problems in design, testing, and evaluation of system properties, such as reliability, and security. It is an exciting area to work in, one that has immediate impact on the technology that shapes society today."

The Illinois Curricula

Because of the fundamental nature of the subject of electromagnetics (EM) for electrical engineering as well as for computer engineering, a course on it is required in both programs. For the *electrical engineering* program, the core curriculum focuses on fundamental electrical engineering knowledge: circuits, systems, electromagnetics, solid state electronics, computer engineering, and design. A rich set of elective courses permits students to select from collections of courses in seven areas of electrical and computer engineering: bioengineering, acoustics, and magnetic resonance engineering; circuits and signal processing; communication and control; computer engineering; electromagnetics, optics, and remote sensing; microelectronics and quantum electronics; power and energy systems. For the *computer engineering* program, the core curriculum focuses on fundamental computer engineering knowledge: circuits, systems, electromagnetics, computer engineering, solid state electronics, and computer science. A rich set of elective courses permits students to concentrate in any subdiscipline of computer engineering including computer systems; electronic circuits; networks; engineering applications; software, languages, and theory; and algorithms and mathematical tools.

We shall hereafter use the term, "electrical and computer engineering," to mean the totality of the three engineering disciplines, "electrical," "electronics," and "communications," and the "computer engineering" discipline, in the Indian system.

ON THE APPROACH USED IN THIS BOOK FOR TEACHING ELECTROMAGNETICS

Electromagnetics Courses and Textbooks

In the context of a course offering or the title of a textbook, the term, "electromagnetics," is freely interchanged with "electromagnetic theory," "electricity and magnetism," "electric and magnetic fields," "electromagnetic fields," "electromagnetic fields and waves," and so on. 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.

This book, a one-semester book, belongs to category 3. The teaching of the course, using books in categories 1 and 2 is heavy on static electric and magnetic fields prior to introducing Maxwell's equations for time-varying fields and wave propagation. As explained in the preface, this book deviates from that approach, with the deviation originating in 1977, by introducing Maxwell's equations for time-varying fields at the outset.

About Electromagnetics

By the very nature of the word, *electromagnetics* implies having to do with a phenomenon involving both electric and magnetic fields and furthermore coupled. This is indeed the case when the situation is dynamic, that is, time-varying, because time-varying electric and magnetic fields are interdependent, with one field producing the other. In other words, a time-varying electric field or a time-varying magnetic field cannot exist alone; the two fields coexist in time and space, with the space-variation of one field governed by the time-variation of the second field. This is the essence of Faraday's law and Ampere's circuital law, the first two of the four Maxwell's equations.

Faraday's law says that a time-varying magnetic field gives rise to an electric field, the space-variation of which is related to the time-variation of the magnetic field. Ampere's circuital law tells us that a time-varying electric field produces a magnetic field, the space variation of which is related to the time-variation of the electric field. Thus, if one time-varying field is generated, it produces the second one, which, in turn, gives rise to the first one, and so on, which is the phenomenon of electromagnetic wave propagation, characterized by time delay of propagation of signals. In addition, Ampere's circuital law tells us that an electric current produces a magnetic field, so that a time-varying current source results in a time-varying magnetic field, beginning the process of one field generating the second.

Only when the fields are not changing with time, that is, for the static case, they are independent; a static electric field or a static magnetic field can exist alone, with the exception of one case in which there is a one-way coupling, electric field resulting in magnetic field, but not the other way. Thus, in the entire frequency spectrum, except for dc, all electrical phenomena are, in the strictest sense, governed by interdependent electric and magnetic fields, or electromagnetic fields. However, at low frequencies, an approximation, known as the qusistatic approximation, can be made in which the time-varying fields in a physical structure are approximated to have the same spatial variations as the static fields in the structure obtained by setting the source frequency equal to zero. Thus, although the actual situation in the structure is one of electromagnetic wave nature, it is approximated by a dynamic but not wavelike nature. As the frequency becomes higher and higher, this approximation violates the actual situation more and more, and it becomes increasingly necessary to consider the wave solution.

Historical Development of Technologies and Teaching of Electromagnetics

Historically, the development of major technologies based on Maxwell's equations occurred in the sequence of electrically and magnetically based technologies (electromechanics and electrical power) in the nineteenth century; electronics hardware and software in the twentieth century; and photonics technologies, entering into the twenty-first century. The teaching of electromagnetics evolved following this sequence, that is, beginning with a course on electrostatics, magnetostatics, energy and forces, and in some cases quasistatic fields, followed by Maxwell's equations for time-varying fields and an introduction to electromagnetic waves. This course was then followed by one or more courses on transmission lines, electromagnetic waves, waveguides and antennas. In fact, when I joined the University of Illinois at Urbana-Champaign in 1965, a three-semester sequence of courses in electromagnetics (Electric and Magnetic Fields, Transmission Lines, and Electromagnetic Fields) for a total of nine credit-hours, were required in the Electrical Engineering (EE) curriculum of a total of 145 credit-hours. The treatment of material in this manner in the first course was largely due to development and application of electrical machinery. The course on transmission lines was to extend the low frequency (lumped) circuit theory, into the high frequency regime by beginning with the introduction of transmission line as a distributed circuit. The third course was then based on full electromagnetic wave solution of Maxwell's equations.

Principal Drawback of the Traditional, Inductive, Approach

In 1973, the Computer Engineering curriculum (CompE) was introduced, and the total number of credit-hours were decreased to 124 credit-hours (now 128 credit-hours) for both curricula. Only one course in electromagnetics, the first of the above three-course sequence, was required in both curricula, with the remaining courses moved to elective status. Soon, this was found to be unsuitable, because the course was based on the inductive approach, that is, an approach consisting of developing general principles from particular facts, which in this case was developing complete set of Maxwell's equations beginning with the particular laws of static fields. Since much time was taken up for the coverage of static fields before getting to the complete set of Maxwell's equations, the time was cut short for the more useful material, centered on electromagnetic waves. This principal drawback of the traditional approach of teaching electromagnetics was unnecessarily aggravating for both curricula, because students were already exposed to the traditional treatment in a prerequisite physics course on electricity and magnetism. It was further aggravating for the Computer Engineering curriculum, because generally that was the only EM course they would take, whereas the EE students would take one or more of the remaining courses as electives.

Elimination of the Drawback by Using the Deductive Approach and Implementation

To resolve this problem, without having separate courses for the two curricula (EE and CompE), a new completely revised course was created based on the deductive approach, that is, an approach in which one begins with the general principles that are accepted as true and then applies it to particular cases, which in this case was beginning with the complete set of Maxwell's equations for time-varying fields and then developing their applications, as well as considering special cases of static and quasistatic fields.

Electromagnetic theory, which is extremely elegant in structure and uniquely rigorous in formulation, is a truly fascinating subject. For those interested in getting enlightened from this cultural aspect, the traditional, inductive, approach is the best, which is what I have done with the publication of my first book, *Basic Electromagnetics with Applications*, as early as in 1972, and with which I continue to be fascinated. Practical considerations described above made me stretch this fascination for the benefit of the modern day curricula and write my second book, *Elements of Engineering Electromagnetics*, using the deductive approach. The first edition of this book was published in 1977, only five years after the publication of the first book, "breaking with the tradition." At that time, it was a one-semester textbook. From 1977 to date, this deductive approach served the needs of the Illinois curricula well by imparting to students the elements of engineering electromagnetics that (a) constitute the foundation for preparing the EE majors to take follow-on courses, and (b) represent the essentials for the CompE majors taking this course only. The subsequent editions of the book were expanded for a two-semester coverage, but retaining the deductive approach in the beginning chapters for the first course and adding material in the later chapters for a follow-on elective course for EE students. Thus, the principal drawback of the traditional approach has been eliminated and shown to be successful by the experience of over more than 30 years.

Using the Deductive Approach for Further Benefit in This Book

A significant secondary drawback of the traditional treatment is that, generally, transmission lines are introduced from the circuit equivalent point of view and then followed by the treatment of electromagnetic waves. This creates a lack of appreciation of the fact that transmission lines are actually physical structures in which electromagnetic waves propagate, except that they are represented by (distributed) circuit equivalents, let alone that (lumped) circuit elements themselves arise from approximations of dynamic field solutions for frequencies low enough that wave propagation effects are negligible. From the very outset, including even in the 1972 book, I have always introduced electromagnetic waves first and then only transmission lines from the field aspect, deriving from the field equations the circuit equations and the equivalent circuit. An understanding based on this approach has become increasingly important with the applications extending farther and farther in frequency along the spectrum.

In this book, I have further stretched my fascination with the subject of electromagnetics by taking the usefulness of the deductive approach one step further by following it with the thread of statics-quasistatics-waves. In this treatment, first electromagnetic wave propagation is introduced by solving Maxwell's equations for time-varying fields. This provides appreciation of the fact that regardless of how low the frequency is, as long as it is nonzero, the phenomenon is one of electromagnetic waves, resulting from the interdependence of time-varying electric and magnetic fields. Then, the thread of statics-quasistatics-waves is used to bring out the frequency-behavior of physical structures.

The thread of statics-quasistatics-waves consists of first studying static fields by setting the time derivatives in Maxwell's equations to zero, and introducing the (lumped) circuit elements, familiar in circuit theory, through the different classifications of static fields. Then, quasistatic fields are studied as low-frequency extensions of static fields, as approximations to exact solutions of Maxwell's equations for time-varying fields. For a given physical structure, this is done by beginning with a time-varying field having the same spatial characteristics as that of the static field solution for the structure, and obtaining field solutions to Maxwell's equations containing terms up to and including the first power (which is the lowest power) in frequency, leading to the result that circuit representation for the input behavior of the structure is the same as the circuit representation for the static case. The thread is then continued by discussing that beyond this "quasistatic approximation," the situation requires exact solution by simultaneous solution of Maxwell's equations, leading to waves and the "distributed circuit" concept of a transmission line.

Later on, during the discussion of transmission line analysis, the condition for the validity of the quasistatic approximation, which is that the dimensions of the physical structure are small compared to the wavelength corresponding to the frequency of operation, is derived, by considering the approximation of the exact solution for low frequencies. In this manner, it becomes quite clear that, along the frequency spectrum, the quasistatic behavior approached from the static (zero frequency) limit as an extension of the static behavior to dynamic behavior of first order in frequency is the same as the low-frequency behavior approached from the other (higher frequencies) side, by approximating the exact dynamic solution for low frequencies. This very important concept is not always clearly understood or appreciated when the inductive approach is employed.

WHY IS EM FUNDAMENTAL TO ELECTRICAL AND COMPUTER ENGINEERING?

IEEE Logo

Very often, the question is asked why one should study EM as a required course for all branches of electrical and computer engineering. In 1963, the American Institute of Electrical Engineers (AIEE) and the Institute of Radio Engineers (IRE) were merged into the Institute of Electrical and Electronics Engineers (IEEE). The IEEE is a global nonprofit organization with over 375,000 members. It is "the world's leading professional association for the advancement of technology." The IEEE logo or badge is a merger of the badges of the two parent organizations. It contains a vertical arrow surrounded by a circular arrow, within a kite-shaped border. No letters clutter the badge because a badge without letters can be read in any language. The AIEE badge had the kite shape which was meant to symbolize the kite from Benjamin Franklin's famous kite experiment to study electricity. The IRE badge had the two arrows that symbolize the right hand rule of electromagnetism. Alternatively, the vertical arrow can be thought of as representing one of the two fields, electric or magnetic, and the circular arrow surrounding it representing the second field, produced by it, so that together they represent an electromagnetic field.

Whether this logo of IEEE was intended to be a recognition of the fact that electromagnetics is fundamental to all of electrical and computer engineering, it is a fact that all electrical phenomena are governed by the laws of electromagnetics, and hence, the study of electromagnetics is essential to all branches of electrical and computer engineering, and indirectly impacts many other branches. In the following, I present the descriptions of the relevance of EM first in general and then by considering certain specific areas of ECE, listed in alphabetical order. (This material is taken, with some modification from the Indian Edition of *Elements of Engineering Electromagnetics, Sixth Edition*, Pearson Education, 2006.)

General

Many laws in circuit theory are derived from the laws of EM. The increased clock rates of computers dictate that the manipulation of electrical signals in computer circuits and chips be more and more in accordance with their electromagnetic nature, requiring a fundamental understanding of EM. EM includes the study of antennas, wireless communication systems, and radar technologies. In turn, these technologies are supported by microwave engineering, which is an important branch of EM. Traditionally, the understanding of EM phenomena has been aided by mathematical modeling, where solutions to simplified models are sought for the understanding of complex phenomena. The branch of mathematical modeling in EM has now been replaced by computational electromagnetics where solutions to complex models can be sought efficiently. The use of laws of EM also extends into the realms of remote sensing, subsurface sensing, optics, power systems, EM sources at all frequencies, terahertz systems, and many other areas. Understanding of electric fields is important for understanding the operating principles of many semiconductor and nanotechnology devices. Electrical signals are conveyed as electromagnetic waves, and hence, communications, control, and signal processing are indirectly influenced by our understanding of the laws of EM. EM is also important in biomedical engineering, nondestructive testing, electromagnetic compatibility and interference analysis, microelectromechanical systems, and many more areas.

Computer Systems

Computer systems and digital electronics are based on a hierarchy of abstractions and approximations that manage the amount of complexity an engineer must consider at any given time. At first glance, these abstractions might seem to make understanding EM less important for a student or an engineer whose interests lie in the digital domain. However, this is not the case. While the fields, vectors, and mathematical expressions that describe EM structures are somewhat removed from the Boolean logic, microprocessor instruction sets, and programming languages of computer systems, it is essential that computer engineers have both a qualitative and a quantitative understanding of EM in order to evaluate which approximations and abstractions are appropriate to any particular design. Choosing approximations that neglect important factors can lead to designs that fail when implemented in hardware, and including unimportant effects in calculations can significantly increase the amount of effort required to design a system and/or obscure the impact of important parameters. A computer engineer or digital system designer must be able to consider EM effects in order to build systems that meet their design requirements. As technology advances, such cases will become more and more common, if for no other reason than the fact that designers are continually driven to push the limits of a given integrated circuit fabrication technology in order to outperform their competition. To be successful, an engineer must be not only a master of his or her specialty, but an expert in all of the areas of electrical engineering that impact that specialty, including EM.

DSL Systems

Hundreds of millions of digital subscriber line (DSL) broadband access connections are now in use around the globe. Such DSLs use the copper telephone-line twisted pair at or near its fundamental data-carrying limits to effect the broadband service. A twisted pair transmission line can be divided into a series of incrementally small circuits that are characterized by fundamental passive circuit elements of resistance (R), inductance (L), capacitance (C), and conductance (G), sometimes known as the RLCG parameters. These parameters often vary as a function of frequency also, and so such models can be repeated at a set of frequencies over a band of use or interest, which is typically 500 kHz to up to as much as 30 MHz in DSL systems. EM theory and, in particular, the basic Maxwell's equations essentially allow the construction of these incremental circuits and their cascade, allowing calculation of the various transfer functions and impedances and then characterize the achievable data rates of the DSL. Of significant interest is the subsequent use of such theory to model an entire binder of copper-twisted pairs using vector/matrix generalizations of the simple isolated transmission lines. The modeling of "crosstalk" between the individual lines is important to understanding the limits of transmission of all the lines within the binder and their mutual effects upon one another. EM theory fundamentally allows such characterization and the calculation of the impact of the various transmission lines upon one another. EM theory is, thus, fundamental to understanding of and design thereupon of DSL systems.

Electrical Power and Energy Systems

The use of electricity for generation, transport, and conversion of energy is a dominant factor in the global economy. EM theory is an essential basis for understanding the devices, methods, and systems used for electrical energy. Both electric and magnetic fields are *defined* in terms of the forces they produce. A strong grasp of fields is essential to the study of electromechanics—the use of fields to create forces and motion to do useful work. In electromechanics, engineers design and use magnetic field arrangements to create electric machines, transformers, inductors, and related devices that are central to electric power systems. In microelectromechanical systems (MEMS), engineers use both magnetic and electric fields for motion control at size scales down to nanometers. At the opposite end of the size scale, electric fields must be managed carefully in the enormous power transmission grid that supplies energy to cities and towns around the world. Today's transmission towers carry up to a million volts and thousands of amps on each conductor. The lines they carry can be millions of meters long. EM theory is a vital tool for the design and operation of these lines and the many devices needed to connect to them. All engineering study related to electrical energy and power relies on key concepts from EM theory. In the future, society needs more efficient energy processing, expanded use of alternative energy resources, more sophisticated control capabilities in the power grid, and better industrial processes. EM represents an essential and fundamental background that underlies future advances in energy systems.

Electromagnetic Compatibility

We live in an increasingly "spectrally rich" EM environment. The potential for a product to *interfere with* other devices, or to be *interfered with* by neighboring electronic systems, is ever increasing. Coupled with this is that increasingly stringent RF emission regulatory standards must be satisfied before a product may be marketed. The electrical or computer engineer of today must know how to design "electromagnetically compatible" (EMC) systems that perform their intended function even in the presence of unintended EM radiation from nearby electronic equipment. Likewise, he or she must know how to design systems that do not themselves pollute the EM spectrum further. The only way this can be done is through a solid understanding of electric fields, magnetic fields, electromagnetic wave propagation, signal-coupling mechanisms, and filtering, shielding, and grounding techniques.

High-frequency Electronics

As information technology continues into the realm of ever higher frequencies, circuits and devices must be designed with an ever keener awareness of EM. At frequencies higher than a few gigahertz, electronic devices can no longer be treated as simple lumped components. Rather, they become enmeshed in a complex web of interconnected phenomena—all of them determined by the laws of EM. High frequency means short wavelength, and as wavelength diminishes to the point where it is comparable to integrated circuit dimensions, EM phenomena called *transmission line effects* become critical. These effects include conductor loss, dielectric loss, and radiation loss. They are a signal's worst enemies. The radio-frequency or microwave circuit designer must lay out transmission lines to achieve optimal matching conditions among parts of the circuit and to limit the signal attenuation caused by transmission line effects.

Integrated Circuit (IC) Design

Electrical signals move from one part of an IC to another according to the laws of EM. Unwanted coupling of electrical signals from different parts of an IC can be explained, and solved, only through recourse to fundamental knowledge about EM. Engineers who specialize in both communications and circuits must bring their EM knowledge to bear on their system design. If the components are not electromagnetically compatible, the system will not function.

Lasers, Fiber Optics, and Optoelectronics

During the past few decades, the invention of lasers and low-loss optical fibers has revolutionized the use of optical communication technologies for high-speed Internet. Although stimulated absorption and emission of photons may require a quantum mechanical description of the photon-electron interaction, classical EM plays a crucial role in understanding the system because light follows the theory of EM waves for most of the guided wave phenomena. In the study of optical communication systems, four important areas of devices are required: generation of light (semiconductor lasers, light-emitting diodes or LEDs, and erbium-doped fiber optical amplifiers), modulation of light (electro-optical modulators, electro-absorption modulators, and optical phase modulators), propagation of light (optical fibers, and optical dielectric waveguides), and detection of light (semiconductor photodetectors). The growing demand for ultra-high-bandwidth Internet technologies requires researchers and engineers to develop novel devices for the generation, propagation, modulation, and detection of light. Knowing EM is a necessity because the wave nature of light plays a vital role in all the above devices.

Medical and Biomedical Imaging

Light, and its interactions with biological tissues and cells, has the potential to provide helpful diagnostic information about structure and function. The study of EM is essential to understanding the properties of light, its propagation through tissue, scattering and absorption effects, and changes in the state of polarization. The spectroscopic (wavelength) content of light provides a new dimension of diagnostic information since many of the constituents of biological tissue, such as hemoglobin in blood, melanin in skin, and ubiquitous water, have wavelength-dependent optical properties over the visible and near-infrared EM spectrum. The study of EM has direct relevance to understanding how light interacts with tissue, and novel technology for medical and biological imaging can be developed based on these EM principles.

Mobile Communication

In 1864, Maxwell predicted the existence of the EM waves by logically examining the known experimental laws: Faraday's law, Ampere's law, Gauss' law and the charge conservation law. Maxwell's prediction was verified by Hertz in 1887 when he propagated an electric spark across his laboratory. Within a few years of Hertz's experiment, Marconi demonstrated the potential application of EM waves for communication by successfully propagating a telegraphic signal across the Atlantic. He coined the term "wireless," when he established his Wireless Telegraph and Signal Company in 1897, and wireless communication took off. For many years, radio signals bouncing off the ionosphere became the main carrier of the global communication networks, connecting people and institutions across the continents. In the 1960s, when the world moved into the space age, satellite communication was introduced which offered faster, better and more reliable services. With this new development, the future of wireless communication was considered very promising. However, without much warning, the optical fiber came along. Broader bandwidth, more secure communication and lower costs of the optical systems made satellite communication a less attractive choice. The world seemed to be moving back to cable communication. For the two decades in the 1970s and 80s, wireless almost became obsolete. Then mobile communication appeared and all of a sudden, thanks to the miniaturization of the devices, we are in the era of personal communication. Wireless is back. New applications are coming out almost every month. It now seems that people's communication needs can no longer be satisfied by mobility alone. They require ubiquity which most likely can only be provided by an innovative wireless environment.

Remote Sensing

The attribute of EM waves to carry energy and information from one point in space (the sender) to another point (the receiver) also makes them a good tool for probing something from a distance. Radar was invented in the 1930s using precisely this property of radio waves (a subset of EM waves). Later, this new application of EM waves developed into a thriving new discipline called "remote sensing." New active and passive devices and systems have been invented to improve remote sensing capabilities. Nowadays data from various remote sensing techniques and equipments provide people with the necessary information to monitor the status of the global environment, information vital to our pursuit of the sustainable development of human society.

Signal Processing

The vast majority of signals processed in high-tech systems and components are EM waves. Engineers must know how to model signal propagation in the physical medium of interest, be it optical fiber, coaxial cable, twisted pair wires, or in the air. Communication system designers employ this knowledge to design algorithms and architectures for transmitting data reliably over a noisy channel.

CONCLUSION

In this preface to the Indian Edition, I have used the word, "fascinating," several times. My dictionary defines "fascinating" as "captivating; enchanting; charming." Whether it is captivating, enchanting, or charming, fascination with the subject of electromagnetics has led me to recognizing a parallel between the guiding principles of my life, the set of four principles from the Upanishads, and the guiding equations of my work, the set of four Maxwell's equations:

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!*

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

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

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

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

Besides the fact that both sets are four in number, the first two of the principles from the Upanishads have to do with mother and father, whose interdependence is the essence of life, whereas the first two of the four Maxwell's equations have to do with the interdependence of dynamic electric and magnetic fields, which is the essence of electromagnetic waves. Whether you will find the subject of electromagnetics fascinating or not, I hope you will find this aspect of electromagnetics, which I call the "Mahatmyam (greatness) of Maxwell's equations," fascinating!

N. NARAYANA RAO