Elements of Engineering Electromagnetics

Sixth Edition

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University of Illinois at Urbana–Champaign

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

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Om Shri Ganeshaya Namaha

Vakrathunda mahaakaaya
Sooryakoti samaprabhaa
Nirvighnam kurumedeva
Sarvakaaryeshu sarvadaa!

You of the twisted trunk and the massive body
With the dazzle and light of millions of suns
Lead me on a path that has no obstacles or hindrances
Clearing the way in all that I do ever, and always!

Saraswathi namasthubhyam
Varadey kaamarupinii!
Vidyaarambham karishyaami,
Siddhirbhavathu me sadaa!!

Oh, Goddess Saraswathi, humble prostrations unto Thee
You are the fulfiller of my wishes!
I start my studies with the request that
Thou shall bestow Thy blessings on me!!

With science, I have gone far.
With science and spirituality, I have gone farther.
With science, spirituality, and service, I shall go even farther.

This Indian edition is 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.

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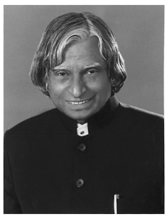


सत्यमेव जयते

A. P. J. Abdul Kalam

Rashtrapati Bhavan
New Delhi 110 004

MESSAGE

I am delighted to know that Prof. Nannapaneni Narayana Rao's sixth edition of the book *Elements of Engineering Electromagnetics* is being brought out as an Indian edition. Prof. Narayana Rao, a fellow alumnus of the Madras Institute of Technology and an eminent teacher, sent me a copy of the U.S. edition of the book when it was published in 2004. I have found the book to be an excellent effort, to be read by all students and teachers of electrical and computer engineering. I was particularly impressed to find that the author has applied the finite element method, normally used by structural engineers, for solving problems of applied electromagnetic field.

It is admirable that with forty-one years of dedicated service at the University of Illinois in the United States, Prof. Narayana Rao has thought of serving the needs of the students of various parts of the world in a significant way through the publication of this Indian edition. The unique method of presentation of the book will enable the students to understand the intricacies of electromagnetics, which is the foundation for the technologies of electrical and computer engineering.

I convey my greetings and best wishes on the occasion of the publication of this Indian edition.

(A. P. J. Abdul Kalam)

14th June 2006
New Delhi

Foreword
by Richard H. Herman

Textbooks are integral to learning, an essential tool students must have to succeed in their studies. Excellent textbooks, such as this one, endure, undergoing periodic revisions to keep step with advances in knowledge. Since its introduction in 1977, the six editions of *Elements of Engineering Electromagnetics* have served engineering students well, clarifying the principles and applications of electromagnetic theory.

This edition is unique, for it is addressed to the students and faculty of India, the birth nation of its author, N. Narayana Rao. For four decades, Professor Rao has been an accomplished professor of electrical and computer engineering at the University of Illinois at Urbana-Champaign.

This edition also includes a significant new section, "Why Study Electromagnetics?" The numerous contributors to this section offer a wide range of answers to the question, drawing on their experiences as teachers, engineers and entrepreneurs. It is a crucial addition, one that students will find most beneficial in broadening their thinking about electromagnetics.

As a public research university with a long history of service to the international community, Illinois has played an important part in the growth of higher education in India. In the 1950s and 1960s, the university applied its longstanding expertise in agriculture and technology to assisting India develop its own academic pursuits and applications of knowledge. Illinois was instrumental in setting up the first Indian Institute of Technology in Kharagpur, which planted the seeds for the high technology revolution driving India today.

Today, the Indian edition of *Elements of Engineering Electromagnetics* continues that tradition in the high-speed era of the Internet and e-learning, a time marked by unbounded academic exploration and rapid transfer of newly acquired knowledge.

I commend Professor Rao for his steadfast concern that he continue to provide engineering students with the most current and accessible textbook in electromagnetics. It is fitting that Professor Rao has prepared this edition during the implementation of the 2005 Indo-US Inter-University Collaborative Initiative in Higher Education and Research, for it is a welcome contribution to the pursuit and sharing of knowledge that Illinois and its counterparts in India have long enjoyed.

RICHARD H. HERMAN
Chancellor, University of Illinois at Urbana-Champaign

Foreword
by Linda P. B. Katehi

Through its six editions, the first one appearing in 1977, *Elements of Engineering Electromagnetics* has provided students with an updated and comprehensive introduction to a major field of electrical engineering. In it, N. Narayana Rao has helped thousands of engineering students master the basic principles and applications of electromagnetic theory.

A distinctive new section of this edition, "Why Study Electromagnetics?" extends the usefulness of this classic textbook by drawing on the experiences of contributors who, as teachers and entrepreneurs as well as engineers, have put electromagnetic theory to work in their professional lives.

It is most fitting that Professor Rao, who has long been professor of electrical and computer engineering at the University of Illinois at Urbana-Champaign, has addressed this new edition to the students and faculty of his birth nation, India. For decades, engineering at Illinois has benefited greatly from the contributions of students and faculty from India. This new edition both grows out of and complements a tradition that has strengthened the study of engineering in both Illinois and India.

I expect the Indian edition of *Elements of Engineering Electromagnetics* to become a valuable resource in engineering education in India.

LINDA P. B. KATEHI
Provost and Vice-Chancellor for Academic Affairs
University of Illinois at Urbana-Champaign

Foreword
by Nick Holonyak, Jr.

After over 50 years of study and work as a semiconductor device scientist and engineer, and after having had the opportunity to witness so many startling developments since the time of John Bardeen and Walter Brattain's original transistor to now the transistor laser (which bears some relationship all the way back to Bardeen and Brattain's point contact transistor), I am able to look back with some depth and perspective at what areas of learning have been vital to us. 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 (EM) in all its many forms that has been so basic, that haunts us and guides us. EM in its many guises is where we first look, and continue to look, to deal with the quantum physics of matter, in our case semiconductors, and to invent a transistor and transistor electronics—not only integrated circuits (ICs) and power devices but also light-emitting diodes (LEDs) and lasers, and now even a transistor laser.

When I look back at how I have learned EM, I see a sort of hit and miss process with constant need for refreshing and patching as I have delved deeper and deeper into semiconductor materials and device study, ranging from germanium transistor problems in Bardeen's laboratory (1952–54) to silicon transistors and thyristors (Bell Labs and General Electric, 1954–63) to the optical domain of LEDs and lasers (General Electric and Urbana, 1960–2006). I regret not having had in my early life an EM textbook such as that of Professor Narayana Rao. My knowledge of EM would be deeper and my life in learning semiconductor device physics would have been smoother, easier, and I think richer. Not only has Professor Rao's book profited from the fact that he is a master teacher, it also has the benefit of coming from the hand of a deep researcher in the field of EM education. His experience and perspective show in his knowledge of EM and how he has been able to bring it all so conveniently to us, from beginner to seasoned expert. He has served all of us by assembling his considerable thought and knowledge, and making EM so clear and so conveniently available. We all need a teacher such as Professor Rao to help us to learn, not just in the beginning but also later in our careers as we review and improve our knowledge. I congratulate Professor Rao for this Indian edition of the book, particularly for the young people entering the study of electronics, dare I say, semiconductor device physics and electronics.

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

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 (EM) in all its many forms that has been so basic, that haunts us and guides us…" —*Nick Holonyak, Jr., in his foreword in this book.*

"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., in the "Why Study Electromagnetics?" section of this book.*

I am grateful to many people, beginning with my parents, and for many things. In the words of the late Gurudeva Sivaya Subramuniyaswami of the Kauai Aadheenam: "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." In the context of this book, I am grateful for the fact that I am the author this book—the Indian version of the sixth edition, and hence the "Indian edition"—and its five predecessor editions, over the span of about 30 years, for introducing electromagnetic theory to students all over the world. In this preface, I would like to reconstruct the trail of this gratitude beginning in the 1950s.

One day during the academic year 1957–58, 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 the 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, 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 the 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 1952–55 and six months of practical training, following 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 to bid a final good-bye to him on the platform. While on the platform waiting for the electric train to arrive from Tambaram, he specifically called 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 (UIUC), as it is now known. Never did I envision that I would be spending 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 holding a 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:

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!

At the conclusion of the response speech on the occasion of the 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, 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 will continue to happen to you to allow you to be even more grateful. Even as late as November 2005, I did not envision the publication of this Indian edition, which includes the new section on "Why Study Electromagnetics?" which I was planning for the seventh edition of the book. It 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 the Amrita Viswa Vidyapeetham of Amma Mata Amritanandamayi Devi, in partnership with the Indian Space Research Organization and the Department of Science and Technology of the Government of India. The MOU has to do with an initiative, known as the Indo-US Inter-University Collaborative Initiative in Higher Education and Research, and allows for faculty from the U.S. to offer courses for e-learning on the EDUSAT Satellite Network, and to pursue collaborative research with India. The Initiative was launched by President Abdul Kalam from New Delhi on the EDUSAT Satellite Network on December 8, 2005.

The term, "Indo-US," prompted me to reflect on my ethnicity, having come from the motherland, India, and become a naturalized American citizen. As a result, I came up with this poem:

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!"

So, as an IndiAmerican, I bring this book to you, as a token of my utmost gratitude to the land of my birth, India, that gave me the guiding principles of my life from the Upanishads, and to the land of my work, the United States of America, where I pursued Maxwell's equations, the guiding equations of this book, as expressed in the dedication in the original sixth edition, reproduced here (see next page)!

In this Indian edition, I also bring to you for the first time in an electromagnetics textbook, or in any textbook that I know, a write-up that addresses an often troublesome matter to the students on why they should study a certain subject. This question is particularly prevalent when it comes to studying electromagnetics. This write-up on "Why Study Electromagnetics?" has been put together by asking for contributions from the faculty and alumni of my department and a former professor of mine at the University of Washington. You will find among them teachers, former teachers, engineers, entrepreneurs, inventors, and even a medical doctor, spanning the gamut of the field of electrical and computer engineering. I am grateful to them all, who by their contributions have done a great service to the academic community. I also express my thanks to James Hutchinson, Editor, Publications, ECE Department, for assisting me in putting together these contributions in a short span of time. You will find that the write-up not only answers the question "Why Study Electromagnetics?" but goes further and serves to educate on the scope of the field of electrical and computer engineering,

Om Shri Ganeshaya Namaha

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

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

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

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

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

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

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

and on the strength of this Jordan-built Department of Electrical and Computer Engineering, which has been my work-home for the past 41 years!

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—a facility 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, halfway around the world from you! And I am pleased and proud to bring to you, the "young minds" of our motherland, this book from this "Temple of Electrical and Computer Engineering!"

Having reconstructed and told you about the trail of gratitude, I shall now tell you about the evolution of this book, beginning with the first edition, published in 1977.

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

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

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

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

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

Part I, entitled "Essential Elements for Electrical and Computer Engineering," is comprised of the first six chapters. These chapters contain essentially the material in Chapters 1–6 and 8 of the fifth edition, except that the organization and treatment of topics is tilted more toward time-varying fields, compared with the fifth edition. Part II, entitled "Essential/Elective Elements" to indicate that they are essential or elective, depending upon the needs of the curriculum, comprises the next five chapters. Chapters 7, 8, 9, and 10 are the same as Chapters 7, 9, 10, and 11, respectively, in the fifth edition, except that I have added the topic of pulses on lossy lines in Chapter 7. Chapter 11, an expanded version of Chapter 12 in the fifth edition, includes the analytical technique of separation of variables and the geometrical method of field mapping, in addition to the four numerical techniques in that chapter.

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

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

As in the previous editions, a number of teaching and learning aids are employed: (1) examples distributed throughout the text, (2) practical applications of field concepts and phenomena interspersed among presentations of basic subject matter, (3) descriptions of brief experimental demonstrations suitable for classroom presentation, (4) summary of material and review questions (**Q**) for each chapter, (5) drill problems (**D**) at the end of each section, (6) margin notes, (7) keywords

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

I wish to express my appreciation to the more than sixty colleagues at the University of Illinois at Urbana-Champaign who have taught from the six editions of the book during the 29-year period from 1977 to 2006. Thanks are also due to the numerous users at other schools. The evolution of this book would not have been possible without the many opportunities provided to me by the many administrators at the University of Washington and the University of Illinois at Urbana-Champaign from 1958 to 2006. Many individuals in the department have provided support over the years. As always, I am deeply indebted to my wife Sarojini for her continued understanding and patience.

N. Narayana Rao
Urbana, Illinois

About the Author

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

At the University of Illinois at Urbana–Champaign, Professor Rao carried out research in the general area of ionospheric propagation and authored the undergraduate textbook *Basic Electromagnetics with Applications* (Prentice Hall, 1972), prior to the six editions (1977, 1987, 1991, 1994, 2000, and 2004) of this book. The fifth edition was translated into Bahasa Indonesia, the language of Indonesia, by a professor of physics at the Bandung Institute of Technology, Bandung. The Salutation to Lord Ganesha (Om Shri Ganeshaya Namaha) in the dedication, which first appeared in the fifth edition, was inspired in part by Professor Rao's visit in January 1999 to the Bandung Institute of Technology, where the image of Ganesha adorns the entrance to the Institute on Jalan Ganesha.

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

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

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

On March 5, 2004, Professor Rao received the Gnana Ratna (Jewel of Knowledge) Award from His Holiness Sri Sri Sri Viswayogi Viswamjee Maharaj at Viswanagar near Guntur, on the occasion of the sixtieth birthday of the Swamiji, "for rendering special services in his field."

A Tribute to Edward C. Jordan

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

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

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

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

N. Narayana Rao
Urbana, Illinois

About the Illinois ECE Series

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

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

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

Valkenburg, another long-standing faculty member who also served as head and dean, wrote several influential textbooks, including *Network Analysis*, one of the most internationally popular engineering texts of all time, first published by Prentice Hall in 1955 and revised in 1964 and 1974.

It is fitting, then, that the Illinois ECE Series began in 2004 with the sixth edition of N. N. Rao's *Elements of Engineering Electromagnetics,* the special India Edition of which you now hold in your hands. Professor Rao was hired to join the Illinois faculty in 1965 by Jordan. Prentice Hall published the first edition of *Elements* in 1977; by the time of its fifth edition, dedicated in 2000 to none other than Ed Jordan, the text had established an international reputation for its grounding in time-honored practices even as it evolved progressively from one edition to the next. That is the essence of the Illinois Way.

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

Today the department enjoys a longstanding, international reputation as one of the premier places in the world for the study of electrical and computer engineering. As of 2006, ECE faculty members advise and instruct more than 1400 undergraduate and over 550 graduate students, while carrying out research funded at a level of $35 million per year. The department is headquartered in the venerable Everitt Laboratory and enjoys world-class, interdisciplinary, Urbana–Champaign campus facilities such as the Beckman Institute for Advanced Science and Technology, the Coordinated Science Laboratory, the Grainger Engineering Library, the Micro and Nanotechnology Laboratory, the National Center for Supercomputing Applications, and the University of Illinois Research Park. Faculty, students, and alumni of the department have established state of the art in fields ranging from microelectronics and nanotechnology to telecommunications, photonics, signal processing, imaging, electromagnetics, bioengineering, circuits, computer engineering, control systems, and more. A sampling of their achievements follows.

- Professor Josef Tykociner invented a process for making moving pictures with sound. In 1922, he was the first person in the world to demonstrate sound-on-film technology.

- Professor John Bardeen joined the faculty in 1951 after co-inventing the transistor at Bell Labs in 1947. Bardeen would go on to develop the theory of superconductivity at Illinois in 1957. He shared the 1956 Nobel Prize in physics for the invention of the transistor, and the same prize again in 1972 for the theory of superconductivity. He remained on the ECE staff until his death in 1991.
- Professors Floyd Dunn and William Fry conducted pioneering research in the use of ultrasound as a noninvasive diagnostic and surgical tool as early as the 1950s.
- Professor Heinz von Foerster's Biological Computer Lab, now legendary worldwide, was the nerve center of U.S. cybernetics research from 1958–1975, developing some of the world's first parallel computers and prefiguring present-day campus interdisciplinary efforts in bioengineering, cognitive science, art and technology, and human–computer intelligent interaction.
- Alumnus Jack Kilby invented the integrated circuit in 1958 while working for Texas Instruments. Kilby won the 2001 Nobel Prize in physics for his invention.
- Student Dwight Isbell invented the frequency-independent log-periodic antenna in 1959, laying the groundwork for Professor Paul Mayes and graduate student Robert Carrel, who the following year developed the log-periodic resonant-V antenna, which would become the most popular antenna for television reception.
- Professor George W. Swenson established radio astronomy at the University of Illinois in 1959 with construction of the Vermilion River Observatory. Swenson would go on to serve as head of both the EE and Astronomy departments, chair the design group for the Very Large Array, and pioneer techniques and instrumentation in the field of animal telemetry.
- Professor Y. T. Lo created antenna designs that improved the efficiency of giant radio telescopes, military and civilian radar, airborne and space vehicles, and ground-based communication systems during the Cold War.
- Professor C. T. Sah, who was attracted to Illinois in 1962 by Bardeen, pioneered the development of complementary metal oxide semiconductor (CMOS) technology and the theory of MOS transistors, which became the workhorses for chips used in computers as transistors evolved from junction-type integrated circuits to field-effect devices.
- Professors and alumni Donald Bitzer and H. Gene Slottow, along with graduate student Robert Willson, invented the plasma display panel in 1964 as an interface with PLATO workstations. In 2002 they received

an Emmy recognizing the importance of their work to the television industry.

- Alumnus Alfred Cho developed molecular beam epitaxy during the 1970s while working at Bell Labs.
- Professor and alumnus Nick Holonyak Jr., who had been Bardeen's first graduate student at Illinois, joined the ECE faculty in 1964 after inventing the first practical light-emitting diode at General Electric. Holonyak and graduate student Ed Rezek demonstrated the first quantum-well laser in 1977. Holonyak, still an active member of the ECE faculty, won the 2002 National Medal of Technology, the 2003 IEEE Medal of Honor, and the 2004 Lemelson-MIT Prize, among many other honors and awards.

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

INTRODUCTION

Why Study Electromagnetics?

Electromagnetics (EM) is the subject having to do with electromagnetic fields. An electromagnetic field is made up of interdependent electric and magnetic fields, which is the case when the fields are varying with time, that is, they are dynamic. An electric field is a force field that acts upon material bodies by virtue of their property of charge, just as a gravitational field is a force field that acts upon them by virtue of their property of mass. A magnetic field is a force field that acts upon charges in motion.

EM is all around us. In simple terms, every time we turn a power switch on, every time we press a key on our computer keyboard, or every time we perform a similar action involving an everyday electrical device, EM comes into play. It is the foundation for the technologies of electrical and computer engineering, spanning the entire electromagnetic spectrum, from dc to light, from the electrically and magnetically based (elctromechanics) technologies to the electronics technologies to the photonics technologies. As such, in the context of engineering education, it is fundamental to the study of electrical and computer engineering, as conveyed by the following PoEM, which I composed some years ago:

To My Dear ECE 329 Student
Whether by design or accident
You might be wondering why you should study EM
Okay, let me tell you about it by means of a 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
Whether by design or accident
My Dear ECE 329 Student.

ECE 329 is the course at the University of Illinois at Urbana-Champaign (UIUC), which is required to be taken by undergraduate students, both in electrical engineering and in computer engineering.

An amusing incident involving the late Edward C. Jordan reveals the fundamental nature of electromagnetics in a lighter vein. One of the earliest postwar research programs to be established at UIUC was a program in radio direction finding (RDF). One of two research programs on the campus sponsored by the Office of Naval Research, it was intended as a basic research program. When the sponsor was asked by the research supervisor, Edward Jordan, what facets of the field might be of particular interest, the answer he received was: “Look, you know Maxwell’s Equations, the Russians know Maxwell’s Equations; you take it from there.” Jordan was amused that it would be difficult to get more “basic” than that. One of the outcomes of that program was research involving the Wullenweber Antenna Array, depicted in Figure 1.

The Wullenweber array, patterned after one developed in Germany in World War II, used 120 antennas and was about 1000 feet in diameter (about 2-1/2 times the size if its German progenitor) and operated over the frequency range 4 to 16 megahertz. Supporting research for more than 25 years from 1955 to 1980, it existed at a field station near Bondville, west of Champaign.

Coming now to the present, for instructional purposes, the Department of Electrical and Computer Engineering at UIUC is divided into the following seven areas:

FIGURE 1
Wullenweber Antenna Array in existence at the Bondville Road Field Station of the University of Illinois at Urbana-Champaign from 1955 to 1980.

Biomedical Imaging, Bioengineering, and Acoustics
Circuits and Signal Processing
Communication and Control
Computer Engineering
Electromagnetics, Optics, and Remote Sensing
Microelectronics and Quantum electronics
Power and Energy Systems

In putting together the material for this chapter for answering the question, "Why Study Electromagnetics?" from the perspective of the various areas, I have requested responses from colleagues at UIUC, alumni of UIUC, and a former professor of mine at my alma mater, the University of Washington. I am grateful to the people, listed below in alphabetical order, along with their affiliations, from whom I have received contributions.

Stephen A. Boppart, Departments of ECE, Bioengineering, and Medicine, UIUC
Andreas C. Cangellaris, ECE Department, UIUC
Nicholas Carter, ECE Department, UIUC
Patrick Chapman and Philip Krein, ECE Department, UIUC
Weng Cho Chew, ECE Department, UIUC
Shun-Lien Chuang, ECE Department, UIUC
John Cioffi, UIUC ECE Alumnus; Hitachi America Professor of Engineering, Stanford University
Eric Dunn, UIUC ECE Alumnus, SAIC
Milton Feng, ECE Department, UIUC
Keith E. Hoover, UIUC ECE Alumnus; Herman A. Moench Distinguished Professor of Electrical and Computer Engineering, Rose Hulman Institute of Technology
Akira Ishimaru, Emeritus Professor of EE, University of Washington
Kyekyoon (Kevin) Kim, ECE Department, UIUC
Zhi-Pei Liang, ECE Department, UIUC
Chao-Han Liu, Emeritus Professor of ECE, UIUC; Chancellor, University System of Taiwan
Naresh Shanbhag and Andrew Singer, ECE Department, UIUC
George W. Swenson Jr., Emeritus Professor of ECE, UIUC
Bruce Wheeler, Departments of Bioengineering and ECE, UIUC
Tony Zuccarino, UIUC ECE Alumnus and Entrepreneur

The contributions follow in the same order as above. Together, they represent views from personalities covering the gamut of the field of electrical and computer engineering.

Stephen A. Boppart, Departments of ECE, Bioengineering, and Medicine, UIUC

Biomedical Optical 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.

Optical biomedical imaging relies on detecting differences in the properties of light after light has interacted with tissue or cells. In addition, novel optical imaging technologies are being developed to take advantage of the fundamental properties of light and EM principles. Optical coherence tomography (OCT) is one such biomedical imaging technology that is rapidly emerging and currently being translated from laboratory-research into clinical practice.

OCT relies on the principle of optical ranging in tissue, and is the optical analogue to ultrasound imaging except reflections of near-infrared (800-1300 nanometers) light are detected rather than sound. Because the wavelength of light is smaller than sound, OCT enables high-resolution imaging that can identify individual cells in tissue to depths of several millimeters. In fact, OCT can be used as a form of "optical biopsy," capturing images that approach that which is commonly viewed in histology, where sections of actual tissue are removed, processed, physically sliced thin, and placed on a microscope slide for viewing by a pathologist. OCT can eliminate the need for removing tissue for examination and for diagnosis.

Since light travels much faster than sound, detection of the reflected EM radiation is performed with interferometry. The use of low-coherence light means that light in the two arms of the interferometer only interfere when their optical pathlengths are matched to within this coherence length. Hence, this enables depth-dependent localization and optical ranging into tissue. Figure 2 shows a basic Michelson-type interferometer, and the interferograms collected using a long-coherence and a short-coherence length light source, assuming a mirror is placed at the focus in the sample arm. By varying the position of the reference-arm mirror, a single depth-scan is acquired. To assemble two- or three-dimensional OCT images, the beam position is translated laterally for subsequent adjacent depth-scans. The figure also shows a cross-sectional OCT image of muscle tissue.

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.

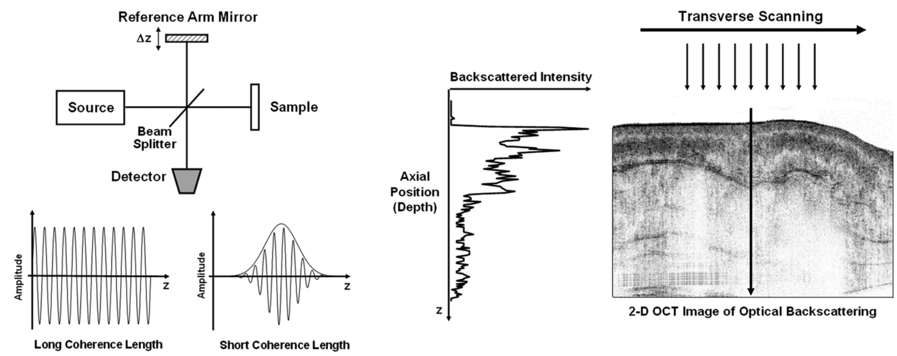


FIGURE 2

Biomedical Optical Imaging.

Andreas C. Cangellaris, ECE Department, UIUC

Learning the Process of Engineering Innovation through the Studying of Engineering Electromagnetics One of the most intriguing, rewarding and challenging experiences of my academic career is the teaching of the fundamentals of EM fields and waves to undergraduate electrical and computer engineering (ECE) students.

What makes it intriguing is the fact that it is these concepts that every ECE student will rely upon as he tries to think through and comprehend the basic principles behind the operation of each and every electronic device, component, circuit or system that constitute the building blocks or the enabling force of the electrical power, communication and computing revolutions of the past century.

What makes it rewarding is the realization that it is these same concepts that will inspire the students' creativity, as they embark on their quest to advance the state of the art and enable new innovative applications of technology in the service of mankind.

What makes it challenging is the short period of time over which an ECE student, on the average, is asked to commit to the study of the fundamentals of engineering EM. Considering how crowded are today's four-year ECE undergraduate programs, most students have only one semester to engage themselves in learning how the fundamental principles of electric and magnetic fields and waves have been exploited and used to fuel some of the most innovative technological breakthroughs in the history of mankind.

Relying upon their early exposure to these ideas through their undergraduate physics preparation, the students are asked to make effective use of the tools of calculus as they embark on the quantitative, applications-driven inquiry of EM fields and waves. In this undertaking, an essential resource is a carefully prepared blueprint of engineering EM—a textbook concise and insightful in the presentation of the fundamentals of EM fields and waves, comprehensive in the discussion of the mathematical methods used for their quantitative investigation, resourceful in the motivation of their practical applications, and inspirational for the student to probe further. This textbook meets these requirements in a masterful way.

The result is the hands-on learning of electric and magnetic fields and the quantitative understanding of what happens as charged particles move around under their influence. For some this learning process is a feast for the intellect, enticing them to a deeper exploration into the fundamental building blocks of matter and, in doing so, enriching their knowledge and skills in physical sciences and mathematics. For others it is an inspirational journey into the understanding of some of the most important forces of nature that govern our existence. For most, it is the process through which they will become familiar with the unifying glue of all technological applications encompassed by what we call today electrical and computer engineering. For all, it is an empowering educational experience on how the investigation, interpretation, appreciation and respectful exploitation of the physical world lead to engineering innovation and through it, to the advancement of mankind.

And this is why every ECE student must study the fundamentals of engineering EM!

Nicholas Carter, ECE Department, UIUC

A Computer Systems Perspective 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 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, but 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.

One example of a situation in which a computer engineer must be familiar with EM is deciding which delay model to use for the wires in a design. Wire delays are a significant component of clock cycle times in modern digital systems, and an engineer must make trade-offs between the accuracy of the model used to predict the delay of each wire and the amount of computation required to evaluate the model. When the rise and fall times of signals on a wire are long compared to the time it takes for an EM wave to travel along the wire, lumped- or distributed-capacitance models, which represent wires as networks of resistors and capacitors, can give accurate estimates of wire delay with relatively little computation. However, as signal rise or fall times start to approach the propagation time of an EM wave along the wire, neglecting wave effects can lead designers to significantly underestimate wire delays, resulting in designs that do not meet their performance requirements and/or do not function correctly.

A rule of thumb is that transmission line (wave) effects should be taken into account whenever a signal's rise or fall time (T_{rf}) is less than $2.5T_p$, where T_p is the amount of time it takes an EM wave to travel from one end of the wire to another. In a vacuum, EM waves travel at $c \approx 300{,}000$ kilometers/second = 30 centimeters/nanosecond, and they travel at about half that rate (15 centimeters/nanosecond) through many of the materials used in integrated circuits. Therefore, wires as short as 1 centimeter may need to be modeled as transmission lines rather than lumped or distributed resistance-capacitance networks if T_{rf} is less than 167 picoseconds (about half of the clock cycle time of a 3 GHz microprocessor), a situation that is becoming increasingly common as clock cycle times become shorter.

Another example comes from the spikes in power consumption and current flow that occur in digital systems at the start of each clock cycle. Typically, digital systems follow a rhythm, in which they are most active immediately after the start of a clock cycle, because the registers in the system have latched their inputs, causing many of the system's gates to compute new outputs. Over the course of the clock cycle, activity decreases as the outputs of more and more gates stabilize, with minimal activity occurring right at the end of the cycle. (Some circuits use clocking methodologies in which registers latch their inputs on both the rising and falling edges of the clock. These circuits see similar rhythms every half-cycle.)

One effect of these activity spikes is that the amount of current flowing through a system's power supply network changes drastically at the start of each clock cycle. This substantial rate of rise of current (di/dt) causes inductive voltage drops across the wires in the power supply, causing the supply voltage seen by the gates in the system to fluctuate, making them operate more slowly than they would with a steady power supply. This can have a significant effect on the performance of a system, requiring designers to consider EM effects carefully when designing power supply networks for digital systems in order to minimize their inductance and thus this di/dt variation in supply voltage.

Another effect is that changes in the amount of current flowing through a wire or the voltage of the wire can induce currents or voltages in other wires through inductive or capacitive coupling (crosstalk). In purely-digital systems, these effects can generally be tolerated as long as the designer follows appropriate design rules, although a substantial understanding of EM is required to develop the design rules for a given integrated circuit fabrication process. However, in mixed-signal systems, which combine digital and analog circuits, crosstalk between wires carrying digital and analog signals is a much more significant issue, and one that must be considered at all stages in the design process. As devices that communicate through wired or wireless networks become more common, mixed-signal systems are becoming increasingly prevalent, making it essential that computer engineers have a solid grounding in EM.

These are but two examples of cases where 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.

Patrick Chapman and Philip Krein, ECE Department, UIUC

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. Several examples follow, showing how EM theory is used in electrical energy applications.

Electromechanics Electric machines consume about 70% of the world's electricity. The water supplies in our cities, the manufacturing processes in our industries, the data equipment in our banks, and a million other vital systems use electric machines as key working components. Today, a typical house is likely to have hundreds of machines, ranging from computer disk drives and DVD players to large motors for appliances and space conditioning. A modern automobile has dozens of electric machines. Hybrid electric vehicles, sure to have a major impact on our economy and environment, use electric motors for propulsion, power steering, cooling, and a host of other functions. Industrial automation and robotics rely on electric machines.

Electrical motors, generators, and actuators are energy conversion devices. The conversions between electrical and mechanical energy take place in coupling fields. Force is produced by interaction of fields with charge or current. Therefore, an understanding of EM fields provides the core of electromechanics, whether the devices are electrostatic, magnetic, piezoelectric, superconducting, or rely on more complicated electromagnetic interactions for their primary operation. The enormous electric generators used in power plants are essential to inexpensive, reliable electricity.

Analysis and design of electric machines based on magnetic fields relies on the EM discoveries of Henry, Ampere, Biot, Savart, Faraday, and many famous physicists and engineers who have worked since then to transform experimental results and mathematical ideas into useful devices. Machines based on electric fields, common in MEMS applications, are analyzed and designed based on the EM discoveries of Franklin, Coulomb, Gauss, and a host of other contributors.

Power Conversion National and international electricity grids are enabled by transformers, which convert voltage and current to preferred levels. Transformers enable the use of long-range high-voltage power transmission—a method that would be inefficient and limited without them. They enable efficient production of low-voltage electricity for digital electronics and home appliances. Transformer design and operation requires a clear understanding of magnetics, including effects such as eddy current and hysteresis loss that are related to fundamental laws of Ampere and Faraday.

More recently, power electronic circuits have become ubiquitous. These circuits use silicon switching devices such as transistors and diodes to manage energy flow. Applications include computer power supplies, automotive systems, alternative energy production, motor controllers, efficient lighting, and portable electronics, to name just a few. These circuits use high-frequency magnetic components, including transformers and inductors for energy storage. Magnetic components are often the largest and most expensive components in power converters. A thorough understanding of magnetic design is fundamental to their application.

In power converter circuit design, EM theory plays another role. Fast switching of large currents and voltages radiates EM energy that interacts with nearby parts. The noise and interference that result are difficult to manage. The concepts of coupling capacitance, mutual inductance, and signal transmission play important roles here. They can only be understood with a proper background in EM theory.

Summary

EM fields and forces are the basis of modern electrical systems. The engineering of electrical energy relies on a thorough understanding of EM. 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.

Weng Cho Chew, ECE Department, UIUC

Electromagnetics EM is the study of the underlying laws that govern the manipulation of electricity and magnetism, and how we use these laws to our advantage. Hence, electromagnetics is the source of fundamental principles behind many branches of electrical engineering, and indirectly impacts many other branches.

For example, many laws in circuit theory can be derived from laws of EM. The increased clock rates of computers make the electrical signals in computer circuits and chips more electromagnetic in nature, meaning that mastering their manipulation requires 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 can also extend into the realms of remote sensing, subsurface sensing, optics, power systems, EM sources at all frequencies, terahertz systems, and many other branches of electrical engineering.

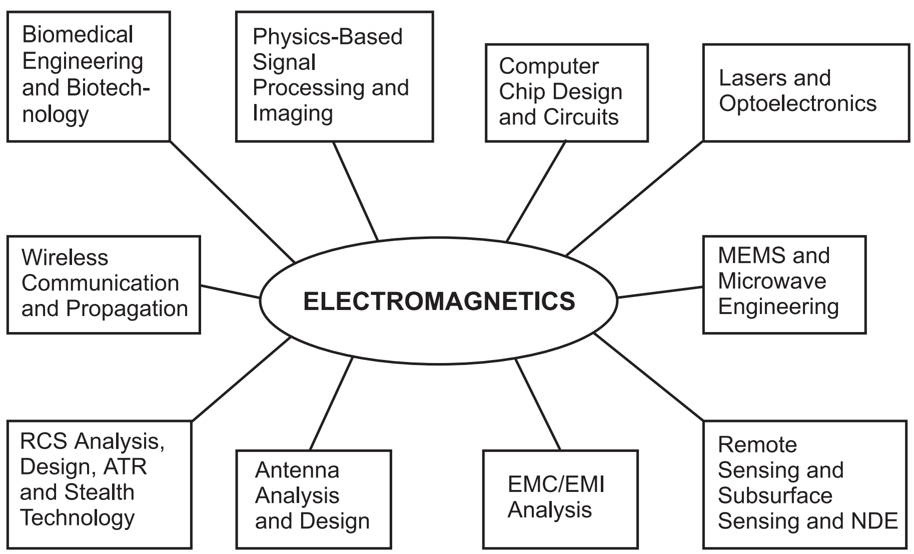


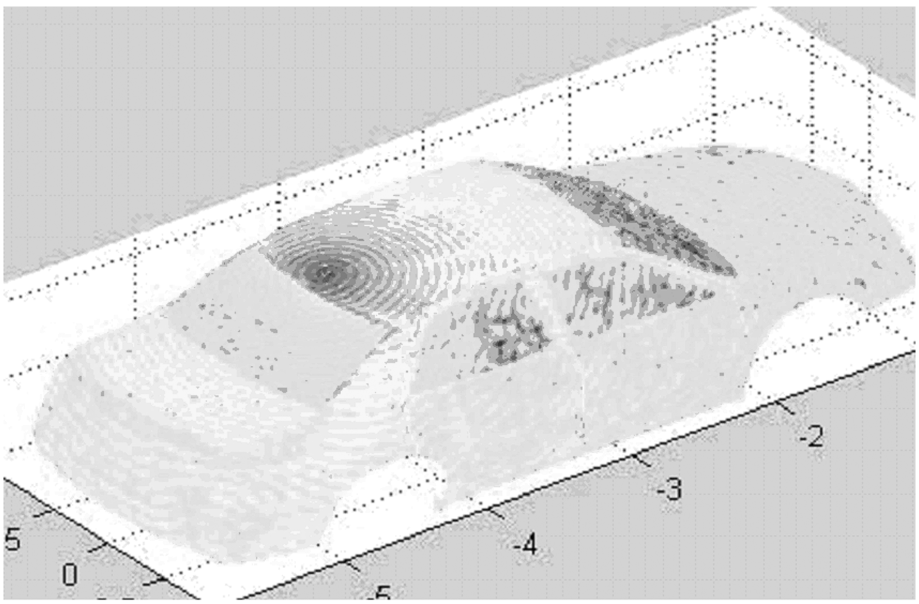
FIGURE 3

Impact of electromagnetics on various areas.

Understanding of electric fields is important for understanding the operating principles of many semiconductor and nanotechnology devices. Many 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, as shown in Figure 3.

Following are three examples in application areas.

1. *Antenna Analysis on Car Roof* Figure 4 shows the analysis of the radiation characteristics of an antenna located on a car. It uses a single-feed microstrip patch antenna that produces a circularly polarized radiation field. The figure shows the induced current on the car body. Circularly polarized antennas are important for communicating with satellites since the ionosphere causes Faraday rotation of the field, making an antenna system nonreciprocal.



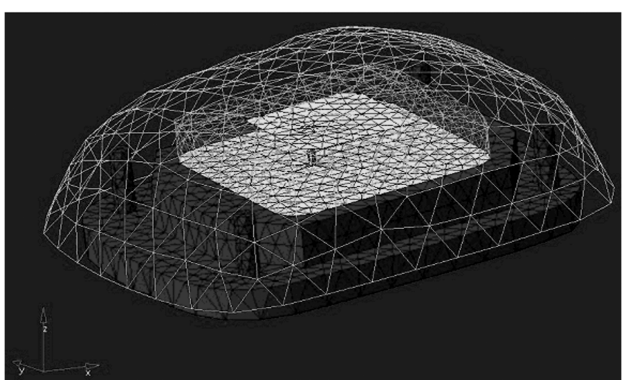


FIGURE 4

Radiation of a microstrip patch antenna on a car roof producing a circularly polarized field (upper figure). The lower figure shows the detail features of the microstrip patch antenna driven by a single probe.

The analysis of the antenna on a car roof needs computational EM analysis to be performed at very small lengthscale to capture the physics of the antenna patch driven by a single feed, as well as at large lengthscale to capture the physics of the wave interaction with the car body.

2. *Crosstalk Analysis in Microchip* Computational EM can be used to model the small lengthscale physics in a microchip. Figure 5 shows the cross talk in a computer chip due to the high clock rate of the chip. High clock rate makes inductive and capacitive coupling between noncontact lines significant. One can see that EM energy is leaking over to the other lines even though only one line is excited in the circuit.

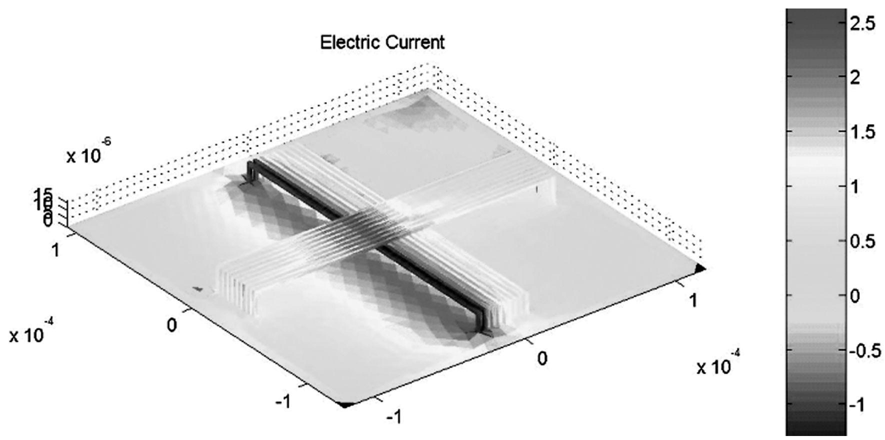


FIGURE 5

Electric current distribution in crisscross lines inside a microchip due to crosstalk at high clock rate of the chip. The frequency under study here is 200 gigahertz.

3. *Subsurface Sensing* EM fields can also be used for remotely sensing objects that cannot be seen with the naked eye. Our eyes can only see the visible spectrum of the EM spectrum. However, using clever imaging techniques, we can

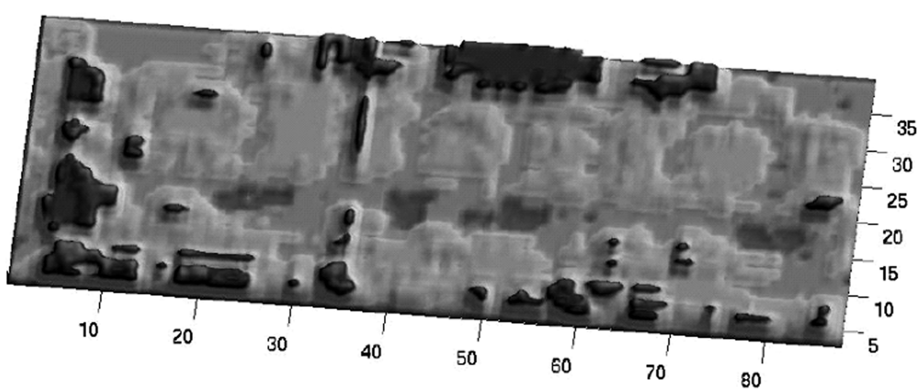


FIGURE 6

Subterranean reconstruction of what is below a parking lot.

use other EM frequencies to "see." Figure 6 shows the subterranean reconstruction of an old parking lot that has been built over a foundry site. Man-made structures such as basement walls and corridors are clearly visible in the reconstruction.

Shun-Lien Chuang, ECE Department, UIUC

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 (LEDs), and erbium-doped fiber optical amplifiers.

The laser structure requires a waveguide or cavity in which light is confined in the form of optical resonator modes, which are the solutions to Maxwell's equations satisfying the boundary conditions specified by the laser cavity. The design of high extraction efficiency LEDs also requires a good understanding of geometric optics.

Modulation of Light Electro-optical modulators, electro-absorption modulators, and optical phase modulators.

These devices require materials with properties, such as refractive index or absorption coefficient, that are controllable by an applied electric field or voltage. A bulk or dielectric waveguide geometry is usually required. The theory of optical waveguides follows from Maxwell's equations.

Propagation of Light Optical fibers, and optical dielectric waveguides.

Optical fiber networks have been installed throughout the world. Understanding the optical guided modes inside optical fibers is very important and follows from Maxwell's equations. Single mode and multimode fibers have also been used for local area optical networks, in addition to single mode fibers for long haul optical communications systems.

Detection of Light Semiconductor photodetectors

Normal incidence and waveguide geometry photodetectors require a good understanding of EM wave theory because light, which is modulated and carries the transmitted data, is illuminated into the active region of the photodetectors to be converted to photocurrents.

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.

John Cioffi, UIUC ECE Alumnus; Hitachi America Professor of Engineering, Stanford University

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. Such high-performance transmission requires a fundamental understanding of the physical channel and in particular the use of EM theory.

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. EM theory is thus fundamental to understanding of and design thereupon of DSL systems.

Of more recent 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. Fundamentally, telephone lines are big antennas, radiating into one another and receiving each other's signals. The other users' signals may be viewed as hostile noise or potentially as helpful signal energy. In either case, the modeling of this "crosstalk" is important to understanding the limits of transmission of all the lines within the binder and their mutual effects upon one another. EM theory again fundamentally allows such characterization and the calculation of the impact of the various transmission lines upon one another. Good methods based on such theory have found that the fundamental limits of transmission on telephone lines of up to one kilometer can be a few hundred megabits per second, essentially enabling the information age to go broadband.

Eric Dunn, UIUC ECE Alumnus, SAIC

For any question that begins with a "why," there are many answers. Here, let me provide you with some food for thought to help you decide for yourself why you want to continue reading this book and making it your bedfellow for the upcoming weeks.

Perhaps you are a curious person and the sheer mystery of electromagnetics provides enough allure to draw you in ...

EM at its deepest level is a very mysterious science. Nobody really knows why EM behaves the way that it does. The closest we can come to explaining how EM behaves is through a small and concise set of equations known collectively as Maxwell's equations. These few brief letters and symbols contain within them *all* of the vast theory of EM. Even today people are coming up with new results and theories from them. The story of how Maxwell's equations historically came to be is well known, but the proof of their validity is only in the vast number of subsequent phenomena they have accurately explained.

Not only is the science behind EM very mysterious at its core, but EM itself is very ubiquitous. The more you study EM, the deeper the mystery goes. For every equation derived, there are always more challenges waiting in the shadows. These can be finding clever ways to solve them, interpret them, or bring them to life. If you are a curious person then you will find the study of EM theory contains plenty of mystery to explore.

Perhaps you are curious, but more hesitant and want to pursue a field of study with less mystery and more practical value to what engineers really work on ...

Understandably a lot of engineers, while they may be curious at heart, are guided by more practical motivations. Some of them may think that since the science of EM does not make the front page headlines of their magazines, it is a dead art. After all, if engineers were using their EM skills, wouldn't it be more obvious? I cannot tell you how many times I have heard this from my students; often in the form of "I'm a computer engineer, why do I need to study EM?"

The truth is that EM has a very far reaching impact. Even if the headlines do not credit EM theory for its accomplishments you can be sure that EM has had its impact. EM plays a significant role in the numerous areas spanning the field of electrical and computer engineering. (See Figure 3). If not convinced that EM theory is being used by many of your colleagues, take a look at the official logo of the Institute of Electrical and Electronic Engineers (IEEE, www.ieee.org). The IEEE is a global nonprofit organization with over 365,000 members. In their own words, they are "the world's leading professional association for the advancement of technology."

You may not know it yet, but that logo is a visual representation of EM theory. The two arrows represent the electric and magnetic fields and the "right hand rule" relationship between them. The outer kite-shaped border is symbolic of Benjamin Franklin's famous kite experiment to study electricity. If an organization as important as the IEEE has chosen EM theory for the design of its logo, then you can be sure that EM theory is still very much alive and being used by many scientists and engineers.

EM theory is a discipline that has been developed for hundreds of years. Engineers use the theory in their work whether they admit it or not. As modern devices become smaller and faster, it is more critical than ever before to have a solid understanding of the underlying physics in order to properly design them. So if you have some curiosity about what EM is, but are hesitant because you wanted to study something more prevalent in the current job market, then hold back no longer. This is one theory that will be around for a long time to come.

Perhaps you are forced to take a course using this book, and have no curiosity about the subject and do not care how many other people or generations have been devoted to this art ...

If you have read this far, then I think there really is some curiosity in you. But I will play along. Let us say you are not curious. And the only reason you are reading this is because you have to. There are still reasons lurking in you for why you should study EM. One way to unlock those reasons is to recognize that there is *always* something to be gained from *every* experience.

Think about your favorite subject. What is that passion which made you want to pursue the study of electrical engineering? EM is a very broad topic. While studying it you are guaranteed to find connections to those subjects which you do enjoy learning. At the least you will gain a richer mathematical background (and all engineering disciplines require some math). You will see analogies between how EM fields interact and other physical phenomena, like sound waves at a rock concert. The lessons you will learn while visualizing the invisible world of EM will help give you the tools that could help you describe other sciences, like the manipulation of complex molecules during a chemical reaction.

Just as buying a new pair of glasses can improve your perception of things around you, the study of EM will help give you focus to better experience and appreciate the world you live in. Go ahead and satisfy your curiosity or be daring and take a risk. Invest your energy into learning this wonderful subject and find out the reason why ***you*** should study EM.

Milton Feng, ECE Department, UIUC

EM for High Frequency Devices and Integrated Circuits As information technology continues into the realm of ever higher frequencies, circuits and devices must be designed with an ever keener awareness of EM. I know this very well from 30 years of personal experience. You see, my group designed and built the world's fastest transistor in the Micro and Nanotechnology Laboratory here at the University of Illinois.

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.

Figure 7 shows one such high-speed circuit fabricated in my lab: a broadband (1 to 11 gigahertz) "quadrature" modulator, composed of indium-phosphide heterojunction bipolar transistors (HBTs). This particular device converts and modulates a baseband (BB) radio-frequency signal into the carrier frequency required for signal transmission. It does so by means of a technique called s*ingle sideband modulation* (SSB). Any time you modulate a signal, you create additional frequencies called *sidebands.* SSB employs quadrature (90°) phasing to suppress unwanted

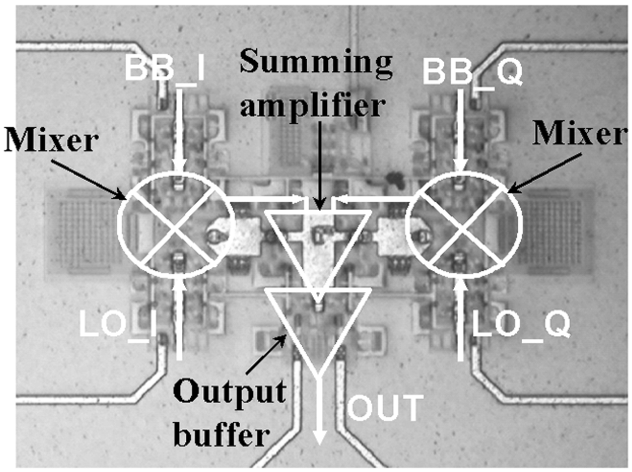


FIGURE 7

Photograph of the fabricated quadrature modulator chip.

sidebands. Our device consists of two mixers, a summing amplifier, and an output buffer. The local oscillator (LO) inputs are sinusoidal waves at the desired carrier frequency, and the baseband inputs are the baseband signals. Here, the 90° difference between the in-phase (I) and quadrature (Q) inputs causes only a single sideband to be transmitted.

To build something like this, first you have to model it, and when it is built you have to characterize it. That requires the solid foundation of EM, as provided in this book, along with some semiconductor device physics in order to understand important device characteristics.

Keith E. Hoover, UIUC ECE Alumnus; Herman A. Moench Distinguished Professor of Electrical and Computer Engineering, Rose Hulman Institute of Technology

Electromagnetics is Essential for Today's Computer Engineer The microcomputer revolution that began in the mid-1970s spawned a new engineering degree in many electrical engineering departments in our nation and around the world. It was called "computer engineering." This program was formed by removing the less "computer-like" courses from the traditional electrical engineering curriculum, such as thermodynamics, analog electronics, electromagnetics, energy conversion, and communications systems, and replacing them with what had traditionally been computer science courses, such as software engineering, computer architecture, operating systems, and data structures.

This new degree was heartily welcomed by industry, because in many of the early companies that made products containing embedded microprocessors, the design department was divided into two distinct camps: the hardware designers (consisting of electrical engineers) and the software designers (consisting of computer scientists). When problems arose as the product neared completion and deadlines became tight, accusing fingers would point back and forth between these two groups, and sometimes violent arguments would erupt, with calls of "I'm sure it's a problem in your hardware design" and "No way! It's a bug in your software!" echoing down the hall.

But with the computer engineer now on the scene, all of this has changed. One computer engineer often designs *both* the hardware and the software for a small embedded product or subsystem of a larger product. Thus, when problems arise, the computer engineer has only himself or herself to point a finger at! One can only hope that the chances of a fight erupting have been considerably diminished! Furthermore, it is likely that the computer engineer, as one who understands the subtle interactions between both the hardware and software, is better equipped to find the problem, which often ends up touching upon *both* hardware and software issues!

The computer engineering degree has indeed become quite popular. In recent years, the enrollment in computer engineering has even surpassed enrollment in the electrical engineering program at some colleges.

OK! I know that I am supposed to be telling you about why you should study EM, not on why you should become a computer engineer! But my point is that these two seemingly unrelated areas are becoming increasingly intertwined. The biggest mistake made by some schools, in their haste to set up a practical computer engineering program back in the late 1970s, was to omit the EM course sequence. Few students complained at the time, because EM has long had the reputation of being highly mathematical and having a steep learning curve. For example, one can start designing a useful digital logic system, such as a digital alarm clock, after only three weeks of lectures; but before one can start designing practical EM devices, such as a slot antenna or the business end of a microwave oven, more than fifteen weeks of lectures are required.

The omission of EM from the computer engineering curriculum may have been pardonable in those early days, when microprocessor clock speeds were below one megahertz, and there were less stringent government regulations regarding radio-frequency (RF) emission. Furthermore, at that time there were not many nearby sources of radio frequencies that were likely to interfere with the operation of an embedded product.

But today things have changed dramatically. Now embedded microprocessor clock frequencies have risen well above 20 megahertz. These higher clock frequencies radiate away from their circuit board more efficiently than did the lower clock frequencies of the earlier microprocessors. This radiated wave is capable of inducing noise in linear traces and loops of neighboring circuit boards, which act like small antennas. If strong enough, the induced noise can cause these neighboring circuits to malfunction. Now increasingly stringent RF emission regulatory standards must be satisfied before a product may be marketed. Furthermore, we are now surrounded by a plethora of nearby wireless RF devices that might interfere with the operation of an embedded design. These include an increasing number of satellite and broadcast radio and TV stations, cellular telephones (which almost everyone now carries, and which periodically transmit even when we are not talking on them), cordless telephones, wireless remote control devices, wireless car keys, wireless internet, and even pill capsules that wirelessly send back pictures of the swallower's colon! In addition to these *intentional* radiating devices, which contain actual radio transmitters, there are also a large number of nearby *unintentional* radiating devices, such as switching dc power supplies, digital audio and video devices that employ the latest digital signal processing techniques, and personal computing devices. All of these unintentional radiating devices require sharp-edged switching pulse trains in order to operate, and they thus generate a wide spectrum of radio frequency interference.

Clearly the potential for a product to *interfere with* other devices, or to *be interfered with* by neighboring electronic systems, is greater than it ever has been. This trend will continue for some time, as systems are clocked at even faster rates. We live in an increasingly "spectrally rich" EM environment. The 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.

These days there are many computer engineers who can design a digital system to perform a given function. However, relatively few of them can design the system so that it is not susceptible to outside RF interference, and so that it also meets the relevant conducted emission (RF emissions that are conducted onto the device's power cord) and radiated emission regulatory standards. Such an engineer is highly sought after and is often able to command a high salary.

It is no wonder that EM courses are once again finding their way back into the computer engineering curriculum! If you are interested in working as an embedded or digital system designer, I hope that you now see how relevant this course can be to your career. Let's face it: This EM course is going to be challenging. It will require regular nightly study and hard work. But I am convinced that if you give it what it takes, you will be rewarded with a deep understanding of electric and magnetic fields, Maxwell's equations, wave propagation, transmission lines, and waveguides. If you let it, this course can provide you with the foundation you need to understand and apply EMC design techniques. When these EMC techniques are coupled with your knowledge of embedded and digital system design, you will be able to perform miraculous and heroic on-the-job design modifications that will amaze your less electromagnetically-literate coworkers!

Akira Ishimaru, Emeritus Professor of EE, University of Washington

Among many subjects taught in university science and engineering courses, electromagnetics stands out as one of the most fundamental for two reasons. First, this is perhaps the only course where the relationships among space, time, spatial and temporal frequencies, spatial vectors, complex vectors, powers, and frequencies in three-dimensional space and time are discussed from unified points of view. Second, EM is based on one of the most fundamental sets of equations in all natural science: Maxwell's equations. The study of EM is to understand the physical meaning of Maxwell's equations as well as to find their solutions, which have applications in almost all modern technologies. The study of EM is therefore, not only of practical importance, but also essential for all engineers.

Kyekyoon (Kevin) Kim, ECE Department, UIUC

The laboratory I have directed for the last 30 years has undergone a few name changes: from the original Charged Particle Research Laboratory, to Fusion Technology and Charged Particle Research Laboratory, to the present Thin Film and Charged Particle Research Laboratory. The name changes have reflected changes in the focus of research both within our lab and in the broader research community. However, note the persistence of the term *charged particle,* reflecting our lab's continuing concern with entities such as electrons, ions, and plasmas—none of which can be understood or manipulated without grounding in the fundamentals of EM.

EM theory provides the basis for our lab's work on some exciting new technologies. For example, a longstanding project has aimed at producing uniform drops of a given material with precisely controlled size and charge, even when the material is insulating in its original state. We first inject charge by inserting a charge-injection needle into the material in liquid phase and invoking either field ionization or field emission. Once the material is charged, we then let the electrical tension forces disrupt the liquid at the charged surface, producing charged drops. We have termed this phenomenon *flow-limited field-injection electrostatic spraying* (FFESS). Figure 8 illustrates the process. After the charged drops have been generated, we employ electromagnetic forces like the Lorentz force to manipulate their trajectories onto a substrate. In this way, we produce patterns, films, nanoparticles, nanofibers, and nanowires for various cutting-edge scientific applications. We have produced nanoparticles whose diameter is one ten-thousandth that of a human hair! We have produced nanofibers of biodegradable materials that can be used to achieve controlled cell proliferation. And we have produced nanowires of copper and silver, typically 100 nanometers in diameter, that can serve as electron emitters in a kind of flat-panel display called the *field-emission display.*

Another project is the development of an advanced, compact, EM railgun (Figure 9) that we can use to accelerate 3 millimeter x 6 millimeter frozen hydrogen pellets to a velocity in excess of 3 kilometers per second, much faster than any high-speed bullet. In this experiment, the armature used to accelerate the hydrogen pellet is a high-density plasma produced by electrically breaking down hydrogen gas. These hypervelocity hydrogen pellets serve to refuel a magnetic confinement fusion device to replenish burnt fuel, which consists of mixtures of hydrogen isotopes.

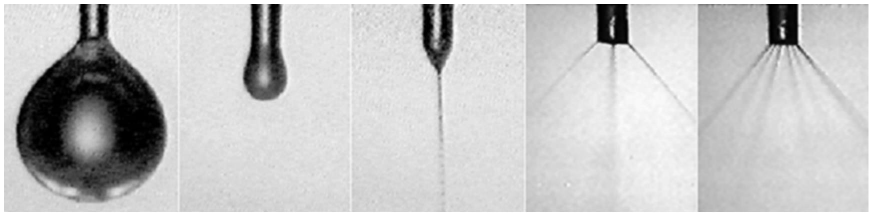


FIGURE 8

Sequential evolution of FFESS with increasing values (left to right) of charging voltage. In these pictures the sprayed precursor solution moves downward off the nozzle. The charged drops resulting from breakup of multijets are nanoscale.

These examples should make clear that EM is an important field with far-reaching impact and influence on many areas of research, including the newly emerging area of nanotechnology. The evolution of our lab over 30 years—keeping abreast of scientific and technological developments while persisting with a focus on charged particles—is testimony to the continuing relevance of EM.

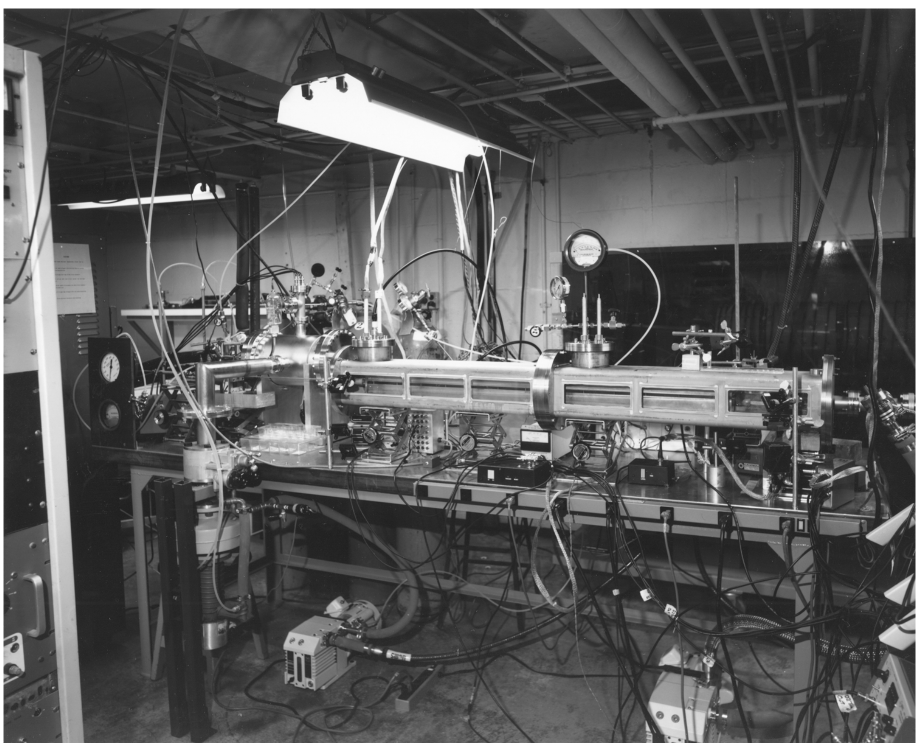


FIGURE 9

Photo of the EM railgun used to accelerate frozen hydrogen pellets.

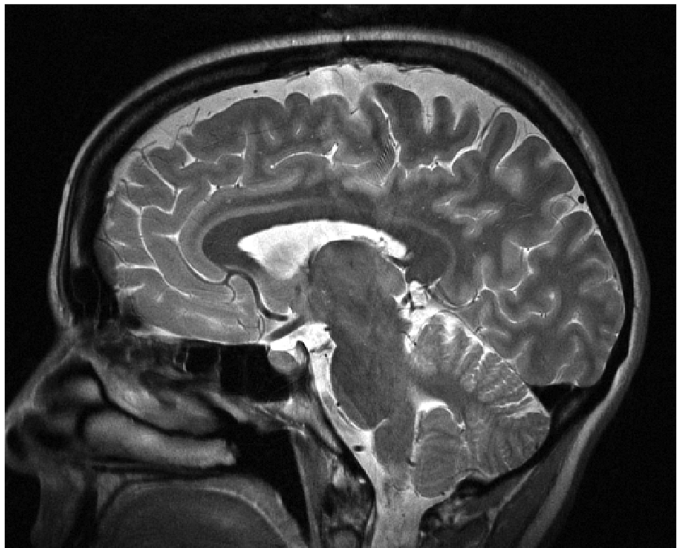


FIGURE 10

Anatomical details of a human head revealed by MRI.

Zhi-Pei Liang, ECE Department, UIUC

Magnetic Resonance Imaging Since its inception in the early 1970s, magnetic resonance imaging (MRI) has developed into a powerful noninvasive imaging modality. With state-of-the-art MRI technology, we can now acquire anatomical, metabolic, and functional information from a biological object independently or simultaneously. An example is shown in Figure 10, which reveals exquisite anatomical details of a human head. With such capabilities, MRI has revolutionized the field of biomedical imaging over the last two decades; thus the 2003 Nobel Prize in Medicine or Physiology was awarded to MRI pioneers Paul Lauterbur of the University of Illinois and Sir Peter Mansfield of the University of Nottingham.

From an engineering standpoint, MRI is a beautiful example of an application of EM. The image formation process uses three magnetic fields to interact with a nuclear spin system for signal generation, detection, and spatial information encoding. Following is a brief overview of this process.

It is well known from college physics that certain nuclei (such as those with odd atomic weights and/or odd atomic number) have an intrinsic angular momentum (often called spin). Nuclear spins have an associated magnetic dipole vector. Under the thermal equilibrium condition, these magnetic dipoles are oriented in random directions and no macroscopic magnetism can be detected. To create an image of an object based on its magnetic dipole vectors, MRI first uses a strong magnetic field (called the $\mathbf{B}_0$ field) to create a nonzero bulk magnetization for the object. It then uses a short-lived, oscillating field (called the $\mathbf{B}_1$ field, or RF pulse because it oscillates in the radio-frequency range) to tip the bulk magnetization away from the direction of the $\mathbf{B}_0$ field. Although magnetic dipole vectors behave quantum-mechanically, the bulk magnetization vector can be accurately described by classical EM theory. This tipped bulk magnetization vector precesses about the $\mathbf{B}_0$ field, thus inducing an electrical signal in the receiver coil placed near the object according to Faraday's law of induction. MRI further imposes on the $\mathbf{B}_0$ field a linear gradient field so that the frequency and/or phase of the MR signals will be linearly dependent on the spatial origin of the signal. This is the well-known spatial information encoding principle invented by Lauterbur. The spatially encoded MR signals can be easily processed using the Fourier transform or Radon transform to generate the desired image.

Although MRI has had tremendous impact on medicine and life sciences over the last two decades, it is still a vibrant field with many opportunities for new technology development. A good background in EM would enable engineering students to be productive in the area.

Chao-Han Liu, Emeritus Professor, UIUC ECE; Chancellor, University System of Taiwan

Wireless—an "Old" Technology Turned Ubiquitous in the Modern World 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.

The basic physics behind wireless communication is EM waves' ability to carry energy and information from one point in space (the sender) to another point (the receiver). This attribute of EM waves 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.

Sensors, algorithms and software developed for remote sensing applications can be used to build the wireless environment in one's home, workplace or any other place. Wireless EM waves will provide access to Internet, video and audio communications, intelligent utility control, entertainment and many other services at any time, anywhere. They will help one do the job better and live better. Just by reading the new IEEE standards for wireless applications, you know this is not futuristic. It is already around the corner.

There is another aspect of the ubiquity of the EM waves. Besides in electrical and computer engineering, they play a role in many other engineering disciplines, including mechanical engineering, chemical and material engineering, environmental and civil engineering, and biomedical engineering. Many cutting-edge developments in those fields—such as MEMS, nanostructures, high speed chips, and biosensors—are related to EM waves.

By now, I hope that I have convinced you that, as a future engineer, you cannot afford not to learn EM, especially about the EM waves. I will also let you in on a secret: it actually is fun to learn how EM waves work, with their mathematical beauty and ingenious engineering applications.

Naresh Shanbhag and Andrew Singer, ECE Department, UIUC

As engineers, one of us specializes in circuit design and the other in signal processing—two fields central to designing high-speed, multimedia networks that are revolutionizing the worlds of information, communication, and entertainment. As cofounders of a high-tech startup company, Intersymbol Communications, Inc., we collaborate on moving our ideas from concept to silicon, from the laboratory into the real world of long-haul and metropolitan area optical networks. As teachers, we prepare our students to play productive roles in this fast-changing world of high technology by grounding them in fundamentals. No field is more fundamental to high technology than EM, and engineers who forget this (no matter what their specialty) do themselves and their clients a disservice.

Take 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.

Take 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. After all, if the components are not electromagnetically compatible, the system will not function.

With our company, we bring EM fundamentals to bear on our respective engineering specialties, and we collaborate to bring mixed-signal (analog and digital) ICs, enhanced with digital signal processing capabilities, to the optical market. A major challenge in optical networks today is to be able to transmit at data rates in excess of 10 gigabits per second over optical fibers, where signals travel at the speed of light but tend to suffer from dispersion. The dispersion occurs because light waves of different wavelengths travel at different speeds, thereby spreading the information over a longer time period as the optical signal travels through a long span of fiber. Intersymbol produces a chip set called the SmartCDR (Clock-Data Recovery), which compensates for dispersion in a 12.5 gigabit per second optical link.

Figure 11 shows where the signal processing comes in. Because of dispersion, what was a clean signal at zero kilometers is almost unrecognizable at 120 kilometers. But an algorithm that incorporates properties of signal propagation (that's EM!)—along with advanced statistical techniques, and implemented with high-frequency mixed-signal ICs—can reconstruct the original signal. That algorithm is embodied in the SmartCDR architecture.

Figure 12 highlights areas in the SmartCDR IC where EM awareness is paramount. Here, the circuit designer had to (1) provide adequate input matching to reduce reflections as analog signals enter the device, (2) model inductors to obtain a high-quality, low phase-noise, voltage controlled oscillator for the clock recovery unit, (3) model the interconnect and terminations in order to guarantee synchronized transmission of the 12.5 gigahertz clock signal from the CRU to the analog–digital converter, and (4) design the output buffers and on-package traces to provide a balanced 32 bit differential, 1.56 gigabit per second interface to the digital chip. Do you see how each of these design challenges required knowledge of EM?

So while many signal processing and circuit design engineers may think they can avoid EM, at Intersymbol we credit our success, in large part, to *engaging* EM, not avoiding it. We are convinced that more opportunity lies ahead for engineers of all specialties who take the same approach.

You have probably heard about *Moore's law,* named after one of Intel's co-founders who, decades ago, accurately predicted the rate of increase in chip density (hence, computing power) which we have enjoyed for so long. It's less likely you have heard about *Snell's law* (introduced in Chapter 8 of this text), which relates angles of incidence and refraction of waves as they move in different media, as happens with optical and electrical signals as they course through fibers, cables, wires; onto and off of boards and chips; and through packages. Advanced high-tech products such as the SmartCDR simultaneously exploit Moore's and Snell's laws in order to achieve system performance that would otherwise be impossible. We believe engineers need to understand EM along with other topics such as IC design, signal processing/communication theory, and VLSI architectures in order to design such products in the future.

And that's why we study EM!

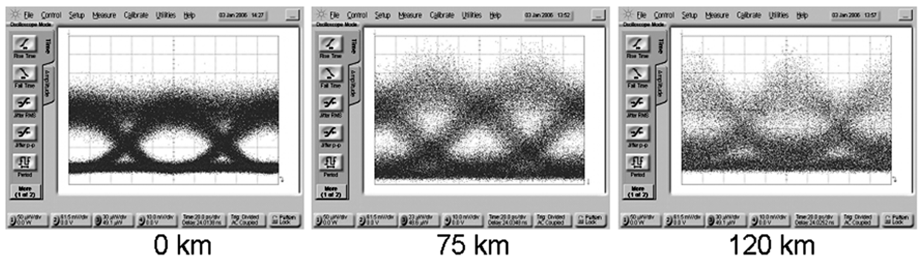


FIGURE 11

Signal dispersion in an optical fiber at 0, 75, and 120 km.

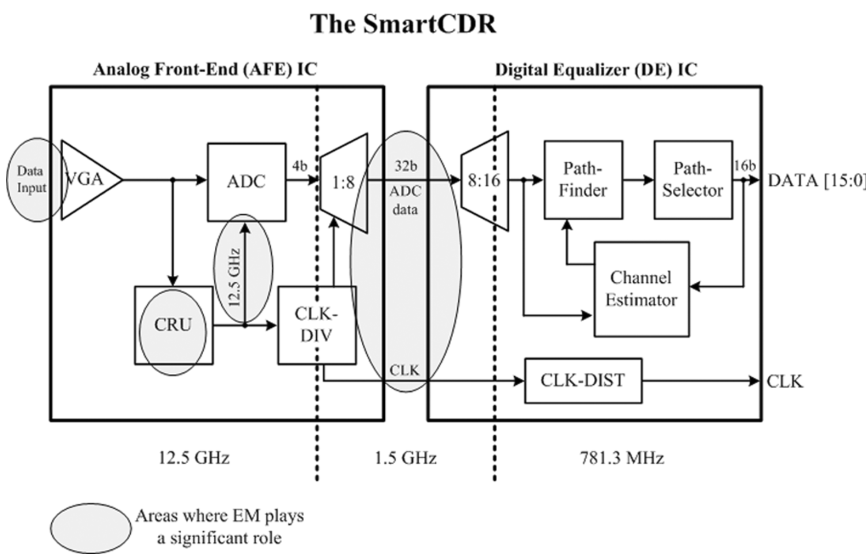


FIGURE 12

Importance of EM in the Intersymbol Communications SmartCDR dispersion compensation chip set for 12.5 gigabits per second optical link.

George W. Swenson Jr., Emeritus Professor of Electrical and Computer Engineering, UIUC

Why do we study EM? The short answer is that EM underlies everything that electrical engineers do in their professional work, and makes possible all the tools of modern society, from the coffee maker in the kitchen to the power generating plant, from the remote car door opener to the propulsion motors of a naval aircraft carrier, from a digital wristwatch to a communication satellite, and on and on.

A more thoughtful answer demands a definition of EM theory. It starts with the observation that, for example, a lightning stroke from cloud to ground can be detected from a distance of scores of kilometers, by human eye or by a device we call a radio receiver. We can also detect a sound by ear that apparently originates in the same lightning stroke. The sound follows the light by a time interval that depends on the distance of the lightning from the observer. Trying to understand the mechanism by which the sound reaches our ears from the distant disturbance, we can use our human senses and experience to visualize how that disturbance shakes the air around it, and how the resulting air vibration propagates through the atmosphere. Our scientific forbears in the 17th and 18th centuries had studied the mechanics of sound transmission through gasses and solids and had formulated a mathematical theory that enables us to predict the behavior of sound waves in most situations. In the case of the radio phenomenon, however, our human senses are of no help; we cannot see, feel, hear or otherwise sense the EM phenomenon (except in the case of light). Other observations suggest that the electromagnetic effect (light) can be observed at a distance even through a vacuum. How can a disturbance at one point in space be manifested at a distant point, apparently instantaneously, when there is no transmission medium? As recently as 125 years ago it was postulated that there existed a mysterious medium permeating space, the luminiferous ether, that sustained electromagnetic waves. Experiments disproving that theory did nothing to explain the EM phenomenon in terms of ordinary human experience. However, brilliant conjectures postulating electric and magnetic fields, and experiments disclosing their interactions with each other, with electric currents in material media, and even with a "virtual" current in a vacuum, had led to a theoretical model that predicts EM phenomena with truly remarkable accuracy and reliability. This theory of electromagnetism is described mathematically and concisely by Maxwell's equations, which form the basis for this book. Thus, while we still cannot see, feel, hear or otherwise sense electric or magnetic fields except through their effects on material substances, we can speak confidently about them, predict their interactions with each other and with material objects, and "understand" them in the abstract.

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. Consider that the human race, physically confined to the inner neighborhood of the Solar System, has no other medium but EM fields by which to know anything about the greater universe. Giant optical and radio telescopes (see Figure 13), which themselves are triumphs of modern technology, make it possible to receive electromagnetic waves from the uttermost limits of the Cosmos and to make images and analyze the substance of the various objects inhabiting it. An intimate knowledge of electromagnetic theory is necessary, not only to design and build the instruments but also to interpret their findings.

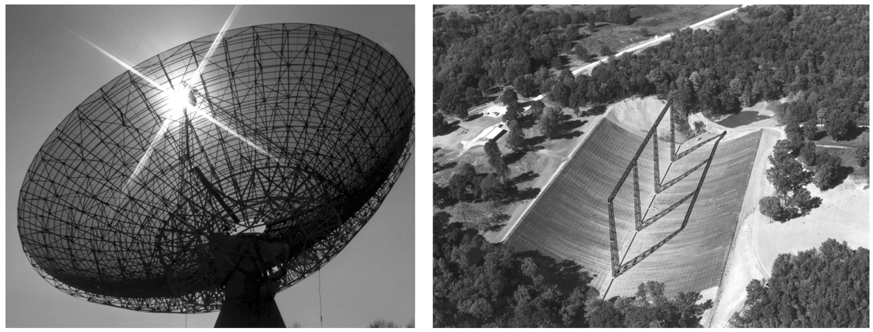


FIGURE 13

Radio telescopes designed and built by George W. Swenson Jr. at the University of Illinois. Left: 120-foot-diameter parabolic dish. Right: 400-foot-diameter parabolic cylinder fashioned out of a stream bed.

Bruce Wheeler, Departments of Bioengineering and ECE, UIUC

The work in neural engineering in my laboratory uses EM in a very routine sense—we use various microscopic, electrical, electronic, and wireless technologies to understand how simple but living models of the brain work. Beyond this, however, the foci of the laboratory are interplays of biology, chemistry, computers, and signal processing. Still, I think it is worth mentioning two examples close to my work for which EM and theory are important.

The first example is relevant to my course, Modeling of Biological Systems. One of the model problems is the formulation of the propagation of electrical signals along axons and dendrites using cable theory, which is essentially the same as the theory of transmission lines with the exception that inductance is negligible. Historically, this model was developed from existing EM theory; it has served to help us understand propagation of action potentials at a very basic level, and failure of conduction such as occurs in multiple sclerosis, a disease where, in the extreme state, changes in membrane resistance cause too rapid a decline (in space) of voltage from one node of Ranvier (an active point of the axon) so that it does not quite reach the next node and then fails to excite the nonlinear process called the action potential. The theory is used to model propagation of signals in dendrites, appearing as recently as March 2006 in an article in *Science,* modeling a novel mechanism by which neural signals are modulated in the brain. Of course, what is research by one investigator quickly becomes teaching material for a professor in a related field.

The second example is one of importance to a research project I participated in on "intelligent hearing aids" and which is generally important to a wide class of biological and biomedical sensors. This is wireless intrabody communication. In the hearing aid example we investigated the efficiency of transmission of signals between hearing instruments in the two ears, as some kind of relatively high data rate communication is needed in order to combine the signals to achieve directivity and frequency selectivity. More generally, wireless communication is used to communicate (reprogram) cardiac pacemakers through the chest and hearing aids from wristwatch-like controllers (low bandwidth). Another example is transmitting power and signal across the skin to operate cochlear implant devices, motivated by a desire not to have a wire penetrating the skin that could also transmit infection. Muscle and vagal nerve stimulators can be implanted and signaled / repowered wirelessly. Under development is the wireless stimulation of the brain for reporting of signals and to achieve a brain-machine interface. In all these cases, EM theory plays a key role: each is much easier imagined than implemented due to very real constraints on power, bandwidth, signal dispersion, and restrictions on device size.

Tony Zuccarino, UIUC ECE Alumnus and Entrepreneur

For many young engineers, the attraction of a high tech career lies in the "higher level" aspects of communication system design—fancy things like network protocols, coding schemes, data compression, software applications, and interfaces. But as an experienced engineer and entrepreneur, I see enormous potential for innovation at a lower level of the system—what we in the broadband communication business refer to as the "physical layer." The physical layer is where the signals move through wired or wireless media according to the laws of EM.

As we progress from sending voice, to data, to high-resolution video over the Internet, both wired and wireless technologies need to evolve to provide a universal and constant data access fabric across the world. The fabric must be fast, reliable, and capacious. This is where the study of EM becomes so crucial to further evolution of the Internet. How will neighboring signals interfere with our carrier of interest? How will our carrier signal interfere with neighboring signals? How do we ensure that data arrives at its destination on time and intact, given such hazards as dispersion, multipath fading, and more?

The answers to these and many other important questions lie in a complete and thorough understanding of EM. That is why success as a signal processing or digital communications engineer can depend heavily on how well one understands EM. For example, say you work in wireless products design. With a solid knowledge of EM, you will play a major role in entire "air to ear" interface, making yourself an indispensable member of the development team, as compared to a role which innumerable other workers can do just as well as you!

CONCLUSION

Now that you have learnt about why study EM, first hand from personalities from the various areas of electrical and computer engineering, let me sum up with the following continuation of the PoEM:

So, you are curious about learning EM
Let us proceed further with the 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 earlier 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.

But then, some of you might say, "Sir, I still have a ProblEM with EM, because it is full of abstract mathematics!" To that I say,

My dear student who is afraid of electromagnetics
Because it appears to be 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 this textbook on Elements of Engineering Electromagnetics
Instead look through the derivations to understand the concepts
Realizing that mathematics is only a means to extend the physics
Think of you 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!