STEFANIA RÖMISCH

Michael Faraday (1791–1867), English chemist and physicist, self-educated from books he was binding to earn a living. An extremely gifted experimentalist, he formulated the law of electromagnetic induction, invented the first dynamo, formulated the fundamental laws of electrolysis, and discovered benzene. Even though he had no formal education, he became the Director of the Royal Institute at age 34 and is certainly one of the greatest scientists ever.

Joseph Henry (1791–1878), American professor of philosophy at Princeton, discovered electromagnetic induction independently of Faraday. He invented and operated the first telegraph and discovered self-inductance. He was the first director of the Smithsonian Institution.

James Clerk Maxwell (1831–1879), Scottish physicist, the greatest name in classical electromagnetism. He unified the four fundamental laws discovered experimentally by his predecessors by adding the abstract notion of displacement current that enables theoretically wave propagation (described in his famous *Treatise on Electricity and Magnetism*). He predicted theoretically the exact speed of light. He was the first professor of experimental physics at Cambridge. A large portion of his life was dedicated to astronomy, and while investigating Saturn's rings, he formulated the kinetic theory of gases. He was one of the rare scientists who was a brilliant mathematician and experimentalist.

Heinrich Rudolf Hertz (1857–1894), German physicist and the first radio and microwave engineer. An ingenious experimentalist as well as theoretician, he demonstrated radio-wave propagation, antennas, microwave sources, polarizers, reflector antennas, first coaxial cable, and many other high-frequency components as they are used today. He discovered the photoelectric effect, for the explanation of which Einstein received the Nobel Prize. He died at the young age of 37 but accomplished more than most long-lived scientists.

Nikola Tesla (1856–1943), American inventor, the son of a Serbian priest and a gifted mother who invented many gadgets to help her do housework. A brilliant experimentalist with no complete formal education, he invented the rotating magnetic field, the induction motor (billions of which are used at any moment), and wireless transmission. Tesla designed the first hydroelectric power plant on the Niagara Falls using his three-phase system for ac generation and transmission. He had more than 100 patents, some of which are still under U.S. government secrecy order.

INTRODUCTORY ELECTROMAGNETICS

To Stefania,
with best wishes for
a long and fruitful
career in EM-related
fields.
I hope you will look
back on our years of
collaboration with fond
memories.
Zoya, 08/2000

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Prentice Hall
Upper Saddle River, New Jersey 07458

Library of Congress Cataloging-in-Publication Data
Popović, Zoya B.
Introductory electromagnetics / Zoya Popović, Branko D. Popović.
p. cm.
Includes index.
ISBN 0-201-32678-7
1. Electromagnetism. I. Popović, Branko D. II. Title.
QC760.P66 1999
537–dc21 99-42828
CIP

Editor-in-chief: Marcia Horton
Acquisitions editor: Eric Frank
Production editor: Stacey Sawyer, Sawyer & Williams
Executive managing editor: Vince O'Brien
Art director: Accurate Art
Cover design: Bruce Kenselaar
Manufacturing buyer: Beth Sturla
Composition: Integre Technical Publishing Co., Inc.
Assistant vice president of production and manufacturing: David W. Riccardi

Prentice Hall

Upper Saddle River, New Jersey 07458

Printed in the United States of America

10 9 8 7 6 5 4 3 2

ISBN 0-201-32678-7

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall of Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall (Singapore) Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

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Preface

This text is primarily an intermediate level one-semester textbook in electromagnetic fields, but it can also be used as a two-quarter or two-semester text. Although vector calculus and basic physics are prerequisites, the book is practically self-contained. It is written for engineering and physics students, focusing on physical principles but also applying them to examples from engineering practice.

Below are some points we followed in writing *Introductory Electromagnetics*.

1. The electrical-engineering curricula in most schools are expanding every new academic year. Fundamental subjects, such as electromagnetics, are being covered with fewer hours and in some schools are even being eliminated. Although we believe that this does not benefit future electrical engineers, it is a reality one has to accept. Therefore, we have carefully selected the topics covered in the text to reflect current needs and have stripped it of all less important details.
2. Computers and software tools are now available for solving a large variety of problems. Thus, we feel that it is imperative for future engineers to understand the problems, not so much to be able to perform analytical manipulation of the equations. This textbook stresses the physical basis of applied electromagnetism, including only the necessary minimum of mathematics, which is derived as needed.

3. This text is oriented toward explaining concepts related to what electrical engineers use most frequently—circuit theory. It is our experience that students at the junior level have a better knowledge of circuits than of mathematics and that they need to develop an understanding of where circuit theory comes from. After grasping Kirchoff's and Ohm's laws and understanding distributed capacitance and inductance (Chapters 1 to 17), students learn how circuit theory can be expanded to transmission-line theory, or the wave equation in one dimension (Chapter 18). Subsequently, they learn how this current and voltage-based electromagnetic wave theory can be generalized to waves in three dimensions described by the electric and magnetic field vectors (Chapters 19 to 25).
4. This book includes 25 chapters and 8 appendices. Most of the early chapters are short; they get progressively longer as the knowledge base increases. We believe that short chapters, with clearly marked sections and subsections, make the text clearer and are not intimidating to the reader. In addition, this organization will make it easier for instructors to tailor the lectures to meet their needs.
5. The applications of electromagnetic fields in electrical engineering are becoming progressively more versatile. Many books cover applications of electromagnetic theory; however, in this text, we consider a limited number of applications that are carefully chosen in such a way that they can be understood more than just superficially, which can help the reader solve problems he/she may encounter in the future. The applications are grouped in Chapters 11, 17, and 25, and they combine concepts from all the preceding chapters. We strongly believe that real knowledge is acquired by connecting material studied in different chapters and that practical applications naturally integrate this knowledge, giving it a new depth.
6. We agree with those who state that "examples, questions, and problems make a course." For this reason, we include a large number of examples. At the end of each chapter, questions help the reader to grasp the basic concepts. Carefully selected problems (20 to 40 per chapter) follow the questions.
7. In the authors' opinion, it is extremely useful for students to have a supplement with solved problems, so that they can see what a correct solution should be like. Although students would like to have answers or hints to all questions and problems, it is important that they find solutions themselves. We offer a compromise in *Practice Problems and Labs*, an integral but physically separate part of the text. The supplement provides three answers to questions and three results for problems, one of which is correct. (In some instances, a hint how to approach the problem is given instead.) It also contains short introductory chapter summaries of basic physical theory and equations and units needed to solve all problems in that chapter.
8. Our students have asked us to include some simple laboratories that have been offered as part of this course at the University of Colorado. They told us that, when they did the experiments, the equations that we studied in class came to life. Thus, the supplement includes several very simple and inexpensive experiments. The experiments are designed to use equipment that every electrical engineering and physics department already has: simple oscilloscopes, function

generators, multimeters, and power supplies. If the instructor has the energy, time, and interest to have the students perform some or all of these experiments, the students will benefit. If time or equipment for labs is not available, the instructor might consider using selected experiments as demos, topics for independent study, or just examples on the blackboard. The prelab homework problems can be used as regular problems.

9. This textbook is written by two professors who together have a total of 50 years of teaching experience, both in the United States and in Europe. Both are active in applied electromagnetics research, advise about 20 graduate students, and have many industrial collaborators. The book is also written by a father and a daughter, one contributing experience and the other an outlook to the future.

Suggested Syllabi and Use of Text

The authors' experience is that the majority of the material contained in this text can be covered in a standard one-semester course (three hours a week, for 15–16 weeks) or in a two-quarter or two-semester course with a greater total number of hours. The instructor can easily decide which parts of the text to skip, or which problems to incorporate into the lectures, to tailor the course for the particular profile of the school and/or students. Suggested below are syllabi for a one-semester, two-quarter (10 weeks each) and two-semester course.

One-Semester Course Outline

WEEK	CHAPTERS	WEEK	CHAPTERS	WEEK	CHAPTERS
1	1–3	6	13–14	11	22–23
2	4–5	7	15–16	12	23
3	6–7	8	17–18	13	24
4	8–10	9	18–19	14	25
5	11–13	10	19–21	15	Review

Two-Quarter Course Outline

WEEK	FIRST-QUARTER CHAPTERS	SECOND-QUARTER CHAPTERS
1	1–3	17
2	4–5	18
3	6–7	19–20
4	8–9	21
5	10	22
6	11–12	23
7	13–14	24
8	15	25
9	16	Review
10	Review	Review

For a two-semester course, the outline is straightforward: complete coverage of Chapters 1–17 in the first semester and Chapters 8–25 in the second, whereby one lecture every other week could be devoted to review or additional examples or problem solving.

A few additional notes:

Both at the University of Colorado and at the University of Belgrade, recitation sessions exist in addition to the lectures, and they were found to be extremely useful. If they are not available, a heavier load of homework can replace them. In the authors' opinion, out of the available questions and problems (a total of about 1200), the students should be required to answer at least 200 questions and solve 150 problems chosen by the instructor. This would guarantee a reasonable level of understanding and applicational ability.

It might be interesting for the instructors to know that the authors have used the questions in class competitions, as well as in the first part of every test and exam. They have also incorporated one two-hour lab per week at the University of Colorado, where the prelab problems have to be completed by the students before the beginning of each lab, and the lab report consists of answering about a dozen questions during the lab session. We have thoroughly enjoyed the labs and believe the many students who say that they find them very useful.

Acknowledgments

The text obtained its final form during the stay of Branko D. Popović at the University of Colorado as a Visiting Professor. He was kindly asked to teach the junior-level electromagnetic fields course (which Zoya Popović teaches often) using rough drafts of some parts of the book. Thus, both authors were able to obtain precious feedback from the students concerning the book's final organization. We are indebted to Professor Renjeng Su, current Chairman of the Department of Electrical and Computer Engineering at the University of Colorado, Boulder, and to Professor Edward Kuester, for their kind effort to enable us to work on the final version of the book at the same physical coordinates. We also thank the faculty in the electromagnetics group at the University of Colorado—Ed Kuester, K. C. Gupta, John Dunn, and Melinda Piket-May—for many useful suggestions and helpful technical discussions. A former student of Branko Popović in Belgrade, Dr. Branislav M. Notaroš, now a faculty member at the University of Massachusetts, Dartmouth, contributed significantly to the solutions in the workbook. The authors would also like to express their gratitude to graduate students at the University of Colorado—Todd Marshall, Manoja Weiss, Michael Forman, Joe Tustin, Shawn Stone, and Jan Peeters-Weem—for being excellent teaching assistants and helping with the development of the labs and to their administrative assistant Helen Frey for being a savior many times. Zoya Popović thanks her husband Professor Dana Anderson for letting her occasionally try out her EM teaching in the physics department and for his love and friendship. Finally, we thank Olya Popović, our mother and wife, respectively, for making us

who we are and our children, sisters, and grandchildren—Sofia, Milica, Nina, and Lena—for helping us keep things in perspective and for their many smiles.

Boulder, Colorado, July 1999
Zoya Popović, Associate Professor, University of Colorado
Branko D. Popović, Professor, University of Belgrade, Yugoslavia

Note to the Student

To quote one of our students, this book can be summarized as "400 [or so] pages on four equations." It is true that Maxwell's equations can describe all the examples, problems, and applications in this book. However, it is also true that these equations were first derived *experimentally* by Coulomb, Ampère, Faraday, and others. Maxwell added one term in Ampère's law that connected all four equations. Therefore, even though electromagnetics might at times seem theoretical to you, please remember its roots. The mathematical apparatus was introduced *to model the physical properties* of electromagnetic fields in a compact way. Whether you are an engineer or a physicist, you will realize in later years the experimental and practical nature of the material covered in this book. We have tried to help you connect the theory to engineering practice by adding chapters on applications, by providing you with a number of practice problems and labs, and by giving realistic values whenever possible.

We would like to give you a few "tips" for learning this material so that you will gain an operational knowledge that will serve you past the final exam, and, we hope, during your entire career. Please treat these "tips" as suggestions: Everyone finds his/her own way of learning a topic. However, our many years of experience and many successful, but also a few unsuccessful, students have provided us with an overview that can benefit you. (We are also certain that your instructor will add other useful suggestions to this list.) So, here are some "recipes for learning electromagnetics."

- Reread each chapter carefully until you can answer most of the questions at the chapter end. If you understand the questions, you can assume you have a good qualitative understanding of the material. You can treat these questions as a game, and study with a friend.
- Make sure you know the basic formulas by heart. This will make it easier for you to use them and understand them, in addition to exercising your brain a little. Write them down on a sheet of paper that you can refer to if you forget them.
- Make sure you know the *units* for all the quantities, as well as some typical values. For example, you should know that capacitance is given in farads (F) and that you probably cannot go to a store and ask for a 2-farad capacitor off the shelf. In addition, units can help you verify many of your solutions, if you know the relationship among the different units (i.e., if you know the basic laws by heart).
- Draw the problems before doing them—many of them are based on physical objects that can be sketched. You will find that, once you know how to sketch a problem, you are half way to solving it.
- Do not get scared by the math. There are a limited number of mathematical tools that you need for this material, and you will master them by the end of the course. It may be a good idea to read through the math appendices first, although some contain more material than you may need.
- As you are studying, try to think of how the material connects with other courses you have taken or are taking now. This will be relatively easy to do for your circuits classes, but you should be able to explain many things in your other courses as well. For example, if you see a "glitch" on your pulse in a digital circuit, it may come from capacitive coupling between two wires or pc-board traces or from the input capacitance of your oscilloscope. Or, you might see a loading effect on a cable that you have not terminated with the right load. You will probably also gain a better understanding of what linear systems mean fundamentally and how time and frequency domain are connected. These are just a few examples of important fundamental concepts that you will learn in this course and that you will use, in one form or another, throughout your career.
- Start studying on time. (You already know this, but it does not hurt to remind you.) This topic might appear easy in the beginning, but *every chapter builds on the previous one*, and so it is important to keep pace. To help you with this, we made the chapters short (except for a few that are technically not easy to divide).

Finally, remember that many people find this topic extremely interesting—but not until they have learned and understood the basics. After you accomplish that, you will have a powerful tool: not only the knowledge of electromagnetics but also a way of thinking that is different from that used in your other classes, as well as techniques that you will be able to apply elsewhere. We hope you work as hard and enjoy yourselves at least as much as we have while preparing this book.

We would like to thank our students from the University of Colorado and the University of Belgrade for putting up with endless lecture notes, correcting many mistakes (true, for extra credit), and being (mostly) enthusiastic about learning. Special thanks to those many students who took time from their busy job schedules after graduating to give us feedback on how they are using this material at work and to thank us for helping them enjoy their professional lives.

Boulder, Colorado, July 1999
Zoya Popović, Associate Professor, University of Colorado
Branko D. Popović, Professor, University of Belgrade, Yugoslavia

"I keep six honest serving-men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who."

Rudyard Kipling