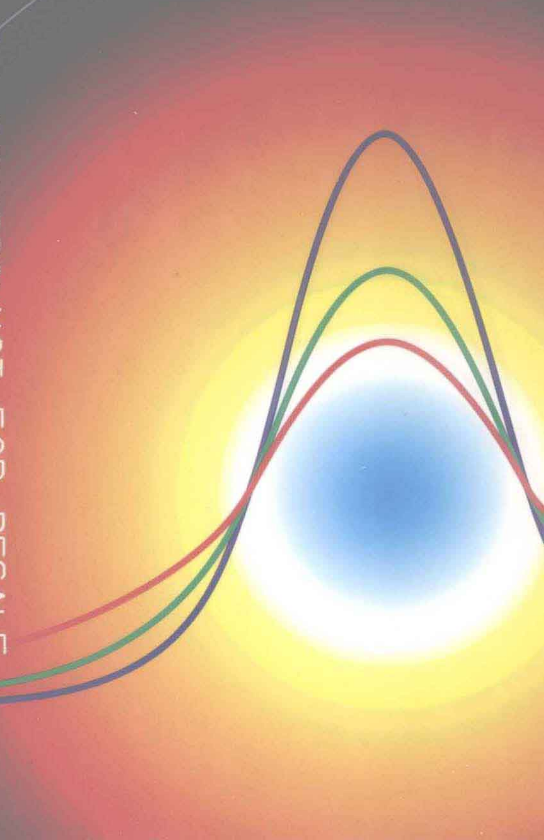
Engineering Electromagnetics

seventh edition

William H. Hayt, Jr.
John A. Buck



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SEVENTH EDITION

William H. Hayt, Jr.
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Purdue University

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McGraw Hill Higher Education

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To Amanda and Olivia

ABOUT THE AUTHORS

William H. Hayt. Jr. (deceased) received his B.S. and M.S. degrees at Purdue University and his Ph.D. from the University of Illinois. After spending four years in industry, Professor Hayt joined the faculty of Purdue University, where he served as professor and head of the School of Electrical Engineering, and as professor emeritus after retiring in 1986. Professor Hayt's professional society memberships included Eta Kappa Nu, Tau Beta Pi, Sigma Xi, Sigma Delta Chi, Fellow of IEEE, ASEE, and NAEB. While at Purdue, he received numerous teaching awards, including the university's Best Teacher Award. He is also listed in Purdue's Book of Great Teachers, a permanent wall display in the Purdue Memorial Union, dedicated on April 23, 1999. The book bears the names of the inaugural group of 225 faculty members, past and present, who have devoted their lives to excellence in teaching and scholarship. They were chosen by their students and their peers as Purdue's finest educators.

A native of Los Angeles, California, **John A. Buck** received his M.S. and Ph.D. degrees in Electrical Engineering from the University of California at Berkeley in 1977 and 1982, and his B.S. in Engineering from UCLA in 1975. In 1982, he joined the faculty of the School of Electrical and Computer Engineering at Georgia Tech, where he has remained for the past 22 years. His research areas and publications have centered within the fields of ultrafast switching, nonlinear optics, and optical fiber communications. He is the author of the graduate text *Fundamentals of Optical Fibers* (Wiley Interscience), which is now in its second edition. When not glued to his computer or confined to the lab, Dr. Buck enjoys music, hiking, and photography.

PREFACE

Preparing a new edition of a textbook is an odd mixture of toil and gratification to their limits. In the midst of long hours and endless minutiae, the acts of incorporating new ideas that augment those already there or that displace those that may have become tiresome provide feelings of relief and accomplishment. Through the effort, there is hope and a growing belief that the new book will be better and more useful.

In the case of electromagnetics, the core subject matter never changes, and so it could be argued that previous treatments that have proven successful are probably best left alone. This was my philosophy when preparing the sixth edition. In this new seventh, I have taken a few more liberties. The older topics, present since the first edition, were reassessed, and a few were either dropped or moved to new locations. These changes were made sparingly, as my intent was to improve the flow of material while attempting to avoid anything that would damage the classic appeal and success of Hayt's original work as it has existed for nearly fifty years.

In recent years, many electromagnetics core courses have shifted their emphasis in the direction of transmission-line theory, in a manner consistent with the rise of computer engineering as a primary component within electrical engineering curricula. This has resulted in the most significant change in our new edition, which is a substantially rewritten (and now independent) chapter on transmission lines. This (the former Chapter 13) is now Chapter 11, and it precedes the chapters on electromagnetic waves. In Chapter 11, transmission lines are treated entirely within the context of circuit theory; wave phenomena are introduced and used exclusively in the form of voltages and currents. Line losses are now covered, along with a more detailed development of the wave equation. Inductance and capacitance concepts are treated as known parameters, and so there is no reliance on any other chapter. This allows transmission lines to be covered as the initial topic in a course, if desired. Field concepts and parameter computation in lines are still present, but now they appear in the early part of Chapter 14, where they play the additional roles of helping to introduce waveguiding concepts while adding perspective to the waveguiding problem. The specific cases of planar, coaxial, and two-wire lines within different frequency regimes are treated as in the earlier editions, and a new section on microstrip line has been added. This material can be covered after Chapter 12 and does not require Chapter 13.

The electromagnetic waves chapters, now 12 and 13 (formerly 11 and 12), retain their independence from transmission-line theory in that one can progress from Chapter 10 directly to Chapter 12. In this way, wave phenomena are introduced from first principles, but within the context of the uniform plane wave. Chapter 12 refers to Chapter 11 in places where the latter may give additional perspective, along with a little more detail. Nevertheless, all the necessary material for learning plane waves without first studying transmission-line waves is present in Chapter 12, should the student or instructor wish to proceed in that order.

The discussion of plane wave reflection and dispersion in Chapter 13 moves directly into Chapter 14, in which waveguiding fundamentals are covered in the light of plane wave reflection models, as well as through direct solution of the wave equation. This chapter retains its original content from the sixth edition, but it now includes an expanded section on optical fibers in addition to the one on transmission-line structures previously mentioned. The last part of Chapter 14 covers basic radiation concepts, a carryover from earlier editions.

The restructuring of the earlier chapters includes the division of the former Chapter 5 (Conductors, Dielectrics, and Capacitance) into two chapters (now 5 and 6) that deal separately with conductors and capacitors. The previous Chapter 6 (which covered field plotting and numerical techniques) has been eliminated, but some of its material has been retained in other chapters. Curvilinear square mapping and discussions of current analogies are now part of the new capacitance chapter (6), and the old section on iterative solution is now part of the Laplace and Poisson equation development in Chapter 7.

A major new supplement to this edition is a CD containing computer demonstrations and interactive programs developed by Natalia Nikolova of McMaster University, and Vikram Jandhyala and Indranil Chowdhury of the University of Washington. Their excellent contributions are geared to the text, and CD icons appear in the margins whenever an exercise that pertains to the narrative exists. In addition, quizzes are provided on the CD to aid in further study. Numerous animations (including a few of my own) are present that help in visualizing many of the phenomena described in the text.

Approximately 40 percent of the problems in the sixth edition have been replaced. In addition to many new problems, I have included several excellent "classic" problems of Bill Hayt's that appeared in the early editions. I decided to revive what I felt were the best and most relevant of these. The drill problems have been reworked and errors have been corrected.

Apart from these changes, the theme of the text is the same as it has been since the first edition of 1958. An inductive approach is used that is consistent with the historical development. In it, the experimental laws are presented as individual concepts that are later unified in Maxwell's equations. After the first chapter on vector analysis, additional mathematical tools are introduced in the text on an as-needed basis. Throughout every edition, as well as this one, the primary goal has been to enable students to learn independently. Numerous examples, drill problems (usually having multiple parts), the end-of-chapter problems, and the material on the media disk, are provided to facilitate this. Answers to the drill problems are given below each problem. Answers to odd-numbered end-of-chapter problems are found in Appendix E. A solutions manual will also be available to instructors. This material, along with the media suite contents and other teaching resources, is also available at the book's website, http://www.mhhe.com/haytbuck. **COSMOS** (Complete Online Solutions Manual Operating System), available to instructors on CD-ROM, contains the entire book problem set, enhanced to include any referenced images or text, as well as the entire solution set for the book. This application will assist instructors in organizing, distributing, and tracking problem sets as they are assigned. Also acknowledged are ANSOFT and Faustus Scientific Corp.

The book contains more than enough material for a one-semester course. As is evident, statics concepts are emphasized and occur first in the presentation. In a course that places more emphasis on dynamics, the transmission lines chapter can be covered initially as mentioned, or at any point in the course. The statics material can be covered more rapidly by omitting Chapter 1 (assigned to be read as a review) and skipping Sections 2.6, 5.5, 5.6, 6.5, 6.6, 7.4 through 7.6, 8.6, 8.7, 9.3 through 9.6, 9.8, and 10.5. A more streamlined presentation of plane waves can be accomplished by omitting Sections 12.5, 13.5, and 13.6. Chapter 14 is intended as an advanced topics chapter, in which the development of waveguide and antenna concepts occurs through the application of the methods learned in earlier chapters, therefore helping to solidify that knowledge. It may also serve as a bridge between the basic course and more advanced courses that follow it.

ACKNOWLEDGMENTS

I am deeply indebted to many students and colleagues who have provided feedback and encouragement prior to and during the preparation of this new edition. In the initial review process, many thoughtful and valuable insights were provided by

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Clive Woods, *Iowa State University*

Their remarks and suggestions affected many aspects of the final product. Errors and inconsistencies in the text and in some of the problems were pointed out in detail in several communications by William Thompson, Jr., Pennsylvania State University. At Georgia Tech, Shannon Madison provided assistance in proofing the drill problems, and Diana Fouts is responsible for the cover illustration and design.

In the four years since the last edition went to press, I received many e-mails from a host of people with questions and suggestions, often about portions of the text that, on further reflection, could have been clearer. It was these acts of calling my attention to the details that have perhaps been of most value in improving the final product. I regret not having been able to answer every message, but they were all considered and acted upon as appropriate. As then, I invite future correspondence, and can be reached at john.buck@ece.gatech.edu.

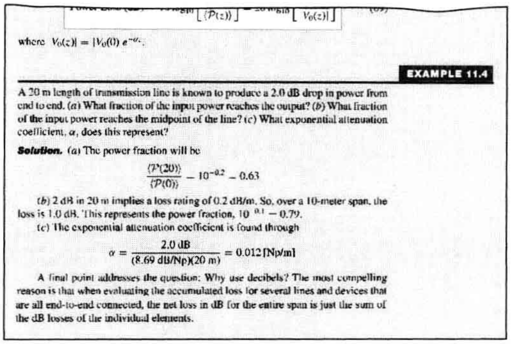
Finally, I acknowledge the project team at McGraw-Hill, whose enthusiasm, encouragement, and support were indispensable. Of these most especially, Michelle Flomenhoft and Carlise Stembridge held everything together and made it all happen. I value my association with them. As with the previous revision, time was too short to complete everything that I had wanted. I am certain that my enthusiasm will be high for a chance at an eighth edition, once rested, and with patience regained by my wife and daughters. The girls, too young to understand why Dad remains hunched over a computer all weekend, have hopefully not grown too old to want him back. I dedicate this book to them.

John A. Buck
Marietta, GA
September 2004

GUIDED TOUR

The main objective of this book is to present electromagnetics in a manner that is clearer, more interesting, and easier to understand. For you, the student, here are some features to help you study and be successful in the course.

Examples: Numerous easy-to-spot examples, which help to reinforce the concepts presented, are integrated throughout each chapter.



where $|V_0(z)| = |V_0(0)|\, e^{-\alpha z}$.

EXAMPLE 11.4

A 20 m length of transmission line is known to produce a 2.0 dB drop in power from end to end. (*a*) What fraction of the input power reaches the output? (*b*) What fraction of the input power reaches the midpoint of the line? (*c*) What exponential attenuation coefficient, α, does this represent?

Solution. (*a*) The power fraction will be

$$\frac{\langle \mathcal{P}(20)\rangle}{\langle \mathcal{P}(0)\rangle} = 10^{-0.2} = 0.63$$

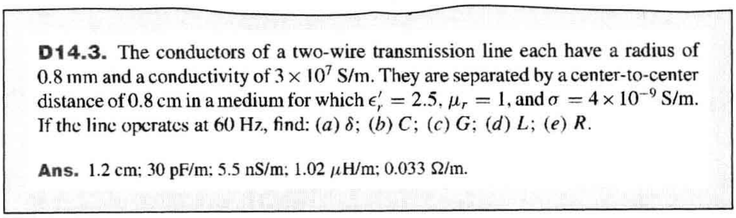
(*b*) 2 dB in 20 m implies a loss rating of 0.2 dB/m. So, over a 10-meter span, the loss is 1.0 dB. This represents the power fraction, $10^{-0.1} = 0.79$.

(*c*) The exponential attenuation coefficient is found through

$$\alpha = \frac{2.0\ \text{dB}}{(8.69\ \text{dB/Np})(20\ \text{m})} = 0.012\ [\text{Np/m}]$$

A final point addresses the question: Why use decibels? The most compelling reason is that when evaluating the accumulated loss for several lines and devices that are all end-to-end connected, the net loss in dB for the entire span is just the sum of the dB losses of the individual elements.

Drill Problems: Many drill problems are also integrated throughout each chapter. These problems, which include answers, serve as a quick way for you to check your understanding of the material.



D14.3. The conductors of a two-wire transmission line each have a radius of 0.8 mm and a conductivity of 3×10^7 S/m. They are separated by a center-to-center distance of 0.8 cm in a medium for which $\epsilon'_r = 2.5$, $\mu_r = 1$, and $\sigma = 4\times10^{-9}$ S/m. If the line operates at 60 Hz, find: (*a*) δ; (*b*) C; (*c*) G; (*d*) L; (*e*) R.

Ans. 1.2 cm; 30 pF/m; 5.5 nS/m; 1.02 μH/m; 0.033 Ω/m.

End-of-Chapter Problems: Each chapter features a wide selection of problems, with answers to selected problems in Appendix E, to give you a chance to practice what you are learning.

14.17 A rectangular waveguide has dimensions $a = 6$ cm and $b = 4$ cm. (*a*) Over what range of frequencies will the guide operate single mode? (*b*) Over what frequency range will the guide support *both* TE_{10} and TE_{01} modes and no others?

14.18 Two rectangular waveguides are joined end-to-end. The guides have identical dimensions, where $a = 2b$. One guide is air-filled; the other is filled with a lossless dielectric characterized by ϵ_r'. (*a*) Determine the maximum allowable value of ϵ_r' such that single-mode operation can be simultaneously assured in *both* guides at some frequency. (*b*) Write an expression for the frequency range over which single-mode operation will occur in both guides; your answer should be in terms of ϵ_r', guide dimensions as needed, and other known constants.

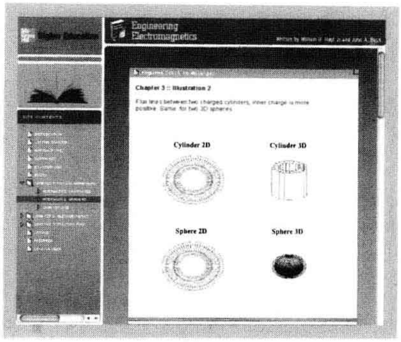
Student Media Suite: Your book comes with a CD-ROM intended to further enhance your understanding of electromagnetics. (Details of the CD-ROM contents appear on the next two pages.) CD icons appear in the text margin throughout the book to indicate when you might use the CD for additional help with that material.

2.4 FIELD OF A LINE CHARGE

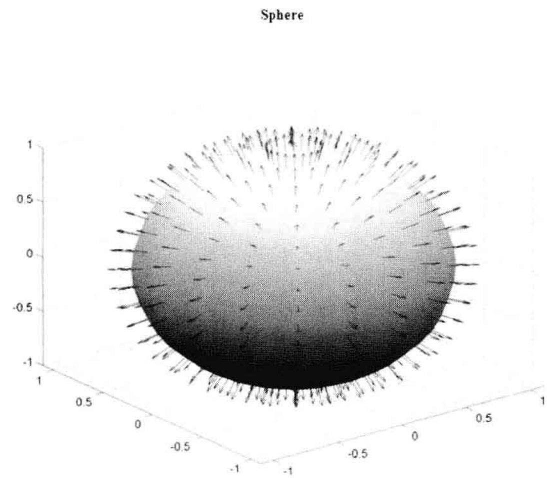
Interactives

Up to this point we have considered two types of charge distribution, the point charge and charge distributed throughout a volume with a density ρ_v C/m^3. If we now consider a filamentlike distribution of volume charge density, such as a very fine, sharp beam in a cathode-ray tube or a charged conductor of very small radius, we find it convenient to treat the charge as a line charge of density ρ_L C/m. In the case of the electron beam the charges are in motion and it is true that we do not have an electrostatic problem. However, if the electron motion is steady and uniform (a dc beam)

Student Media Suite

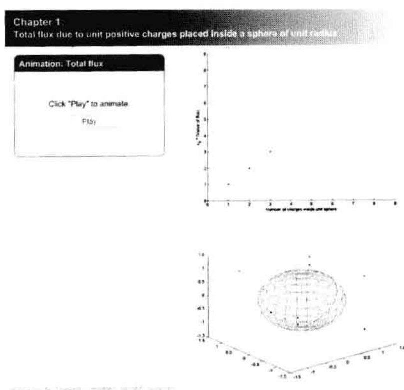


The CD-ROM material was created to provide you additional learning resources for the more difficult electromagnetics concepts. This self-study tool has an easy-to-navigate interface that allows you to look up material by chapter.

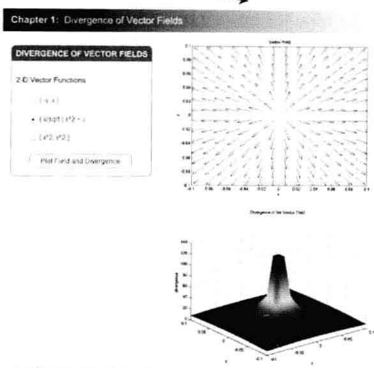


Learning Resource #1—Illustrations: In order to help you to better visualize the concepts, additional illustrations in four colors have been included.

Learning Resource #2—Animations: Numerous animations go one step further by showing you a demonstration of electromagnetic phenomena with Flash animation.



Learning Resource #3—Interactives: The interactives not only allow you to see the concepts, but they also let you physically adjust the variables or the figure itself to see the concepts in action.



Learning Resource #4—Quizzes: To help you further test your understanding, a quick quiz is provided for each chapter. Immediate feedback is given to let you know if you have answered the questions correctly.

QUIZ – CHAPTER 1 (Vector Analysis)

1. The cross product of $8\mathbf{a}_x + 6\mathbf{a}_y$ (first vector) and $9\mathbf{a}_x - 4\mathbf{a}_z$ (second vector) is

Select $72\mathbf{a}_x - 24\mathbf{a}_z$

Select $-24\mathbf{a}_x + 32\mathbf{a}_y - 54\mathbf{a}_z$

Select $72\mathbf{a}_x + 24\mathbf{a}_y + 16\mathbf{a}_z$

Select $24\mathbf{a}_x - 32\mathbf{a}_y + 54\mathbf{a}_z$

2. A vector function whose divergence is 4x could be

Select $4x\mathbf{a}_x$

Select $(4x^2 + y)\mathbf{a}_x$

Select $4x^2\mathbf{a}_x$

Select $(2x^2 - y)\mathbf{a}_x$

3. The gradient of the scalar function xyz is

Select $x\mathbf{a}_x + y\mathbf{a}_y + z\mathbf{a}_z$

Select 0

Select $yz\mathbf{a}_x + xy\mathbf{a}_y + xz\mathbf{a}_z$

Select $xyz\mathbf{a}_x + xyz\mathbf{a}_y + xyz\mathbf{a}_z$

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