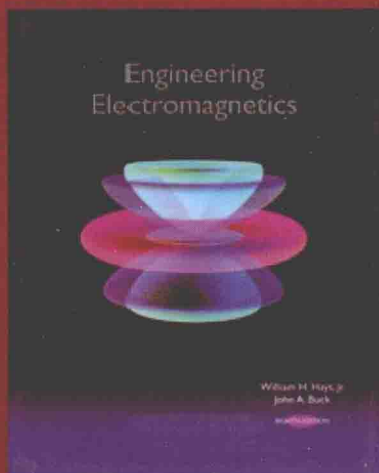


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清华版双语教学用书



# 工程电磁场 (第8版)

Engineering Electromagnetics

(Eighth Edition)

William H. Hayt, Jr. 著  
John A. Buck

袁建生 选译

清华大学出版社

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## ABOUT THE AUTHORS

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**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 28 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. Awards include three institute teaching awards and the IEEE Third Millennium Medal. When not glued to his computer or confined to the lab, Dr. Buck enjoys music, hiking, and photography.

# 序

作者 William H. Hayt, Jr. 教授曾任教于美国普渡大学,其一生获得诸多荣誉,堪称教学名师之典范。请读者在学习该教材之前,一定要阅读作者简介,相信这一定会激发你对 William H. Hayt, Jr. 教授的敬仰和对电磁场学习的兴趣。作者 J. A. Buck 为乔治亚理工学院电气与计算机工程系教授。两位作者合编的该书的第 6 版于 2001 年出版,William, H. Hayt, Jr. 的第 1 版距今已 50 多年。

本教材与国内电子与电气工程专业的本科教材基本一致,其内容满足我国高校教学大纲要求。该书基本概念讲述清晰、注重物理概念、淡化公式推导、图文并茂、定理和重要公式彩色加重印刷;每章后面都配有约 30 道习题。该书写作文笔流畅、可读性好、易理解,学生可以使用该教材进行自主学习,是电磁场或电磁场与波课程的理想教材或参考书。

需要特别指出的是:该书配有学习网站(网址见封底),网站提供了丰富的学习资源和内容,包括图、动画、互动、小测验等,书中页边处给出了网站上对应内容的图标,每当学到图标处时,建议查阅网站相应内容,这对学习非常有益。另外,每章后面的习题采用三级难度分类标识给出每道题的难易程度(题号后的竖条),便于不同学习程度的学生选择习题。

相对于国内相应教材,该书在内容上包含一些工程使用性内容,如不规则形状电极间的电容近似计算方法、PN 结电容、磁路概念、铁磁材料的非线性等内容。该书在内容上的另一特点是简略一些公式推导,加强物理概念讲述,新版本更加如此。例如,新版本删除了求解拉普拉斯方程和泊松方程的分离变量法和差分法等内容,因为此为数学方法,并非物理概念。删除的这些内容放到了网站上供扩展性学习。

该书在内容编排上有独到之处。例如,在静电场部分,将能量与电位的引入结合在一起(第 4 章的题目为能量和电位),突出了电位是电场对单位电荷做功的物理属性,而不是像国内教材强调电位梯度等于电场强度的数学关系;在磁场部分,相对于静电场部分的 5 章编排,该部分仅以两章出现,一章的题目为“恒定磁场”,另一章的题目为“磁场力、材料和电感”,这种编排的综合性与静电场内容编排的分散性形成了明显的反差,且在讲解中多处是通过与静电场类比的形式直接给出结果或结论。

在内容讲解上比较简洁,如仅用了两页就介绍完了磁场能量与求磁场力的虚功法,并且概念和实用性很强,从该节题目上的“磁材料上的力”便可以清楚地表明,虚功法的主要用途是求作用在磁材料上的力,这是利用洛伦兹磁力的表达式求解所不及的。

该书在教学网站提供了教辅资源,包括动画、互动、测验等,并给出了一些利用 Ansoft 等电磁场数值计算软件得到的场图,以及一些问答测试题。

袁建生

清华大学电机与应用电子技术系

2014 年 3 月

# PREFACE

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It has been 52 years since the first edition of this book was published, then under the sole authorship of William H. Hayt, Jr. As I was five years old at that time, this would have meant little to me. But everything changed 15 years later when I used the second edition in a basic electromagnetics course as a college junior. I remember my sense of foreboding at the start of the course, being aware of friends' horror stories. On first opening the book, however, I was pleasantly surprised by the friendly writing style and by the measured approach to the subject, which — at least for me — made it a very readable book, out of which I was able to learn with little help from my professor. I referred to it often while in graduate school, taught from the fourth and fifth editions as a faculty member, and then became coauthor for the sixth and seventh editions on the retirement (and subsequent untimely death) of Bill Hayt. The memories of my time as a beginner are clear, and I have tried to maintain the accessible style that I found so welcome then.

Over the 50-year span, the subject matter has not changed, but emphases have. In the universities, the trend continues toward reducing electrical engineering core course allocations to electromagnetics. I have made efforts to streamline the presentation in this new edition to enable the student to get to Maxwell's equations sooner, and I have added more advanced material. Many of the earlier chapters are now slightly shorter than their counterparts in the seventh edition. This has been done by economizing on the wording, shortening many sections, or by removing some entirely. In some cases, deleted topics have been converted to stand-alone articles and moved to the website, from which they can be downloaded. Major changes include the following: (1) The material on dielectrics, formerly in Chapter 6, has been moved to the end of Chapter 5. (2) The chapter on Poisson's and Laplace's equations has been eliminated, retaining only the one-dimensional treatment, which has been moved to the end of Chapter 6. The two-dimensional Laplace equation discussion and that of numerical methods have been moved to the website for the book. (3) The treatment on rectangular waveguides (Chapter 13) has been expanded, presenting the methodology of two-dimensional boundary value problems in that context. (4) The coverage of radiation and antennas has been greatly expanded and now forms the entire Chapter 14.

Some 130 new problems have been added throughout. For some of these, I chose particularly good "classic" problems from the earliest editions. I have also adopted a new system in which the approximate level of difficulty is indicated beside each problem on a three-level scale. The lowest level is considered a fairly straightforward problem, requiring little work assuming the material is understood; a level 2 problem is conceptually more difficult, and/or may require more work to solve; a level 3 problem is considered either difficult conceptually, or may require extra effort (including possibly the help of a computer) to solve.

As in the previous edition, the transmission lines chapter (10) is stand-alone, and can be read or covered in any part of a course, including the beginning. In it, 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. Inductance and capacitance concepts are treated as known parameters, and so there is no reliance on any other chapter. Field concepts and parameter computation in transmission lines appear in the early part of the waveguides chapter (13), where they play additional roles of helping to introduce waveguiding concepts. The chapters on electromagnetic waves, 11 and 12, retain their independence of transmission line theory in that one can progress from Chapter 9 directly to Chapter 11. By doing this, wave phenomena are introduced from first principles but within the context of the uniform plane wave. Chapter 11 refers to Chapter 10 in places where the latter may give additional perspective, along with a little more detail. Nevertheless, all necessary material to learn plane waves without previously studying transmission line waves is found in Chapter 11, should the student or instructor wish to proceed in that order.

The new chapter on antennas covers radiation concepts, building on the retarded potential discussion in Chapter 9. The discussion focuses on the dipole antenna, individually and in simple arrays. The last section covers elementary transmit-receive systems, again using the dipole as a vehicle.

The book is designed optimally for a two-semester course. As is evident, statics concepts are emphasized and occur first in the presentation, but again Chapter 10 (transmission lines) can be read first. In a single course that emphasizes dynamics, the transmission lines chapter can be covered initially as mentioned or at any point in the course. One way to cover the statics material more rapidly is by deemphasizing materials properties (assuming these are covered in other courses) and some of the advanced topics. This involves omitting Chapter 1 (assigned to be read as a review), and omitting Sections 2.5, 2.6, 4.7, 4.8, 5.5–5.7, 6.3, 6.4, 6.7, 7.6, 7.7, 8.5, 8.6, 8.8, 8.9, and 9.5.

A supplement to this edition is web-based material consisting of the aforementioned articles on special topics in addition to animated demonstrations and interactive programs developed by Natalya Nikolova of McMaster University and Vikram Jandhyala of the University of Washington. Their excellent contributions are geared to the text, and icons appear in the margins whenever an exercise that pertains to the narrative exists. In addition, quizzes are provided to aid in further study.

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), end-of-chapter problems, and material on the web site, 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 F. A solutions manual and a set of PowerPoint slides, containing pertinent figures and equations, are available to instructors. These, along with all other material mentioned previously, can be accessed on the website:

[www.mhhe.com/haytbuck](http://www.mhhe.com/haytbuck)

I would like to acknowledge the valuable input of several people who helped to make this a better edition. Special thanks go to Glenn S. Smith (Georgia Tech), who reviewed the antennas chapter and provided many valuable comments and suggestions. Detailed suggestions and errata were provided by Clive Woods (Louisiana State University), Natalya Nikolova, and Don Davis (Georgia Tech). Accuracy checks on the new problems were carried out by Todd Kaiser (Montana State University) and Steve Weis (Texas Christian University). Other reviewers provided detailed comments and suggestions at the start of the project; many of the suggestions affected the outcome. They include:

Sheel Aditya – Nanyang Technological University, Singapore  
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Denise Thorsen – University of Alaska Fairbanks  
Chi-Ling Wang – Feng-Chia University

I also acknowledge the feedback and many comments from students, too numerous to name, including several who have contacted me from afar. I continue to be open and grateful for this feedback and can be reached at [john.buck@ece.gatech.edu](mailto:john.buck@ece.gatech.edu). Many suggestions were made that I considered constructive and actionable. I regret that not all could be incorporated because of time restrictions. Creating this book was a team effort, involving several outstanding people at McGraw-Hill. These include my publisher, Raghu Srinivasan, and sponsoring editor, Peter Massar, whose vision and encouragement were invaluable, Robin Reed, who deftly coordinated the production phase with excellent ideas and enthusiasm, and Darlene Schueller, who was my guide and conscience from the beginning, providing valuable insights, and jarring me into action when necessary. Typesetting was supervised by Vipra Fauzdar at Glyph International, who employed the best copy editor I ever had, Laura Bowman. Diana Fouts (Georgia Tech) applied her vast artistic skill to designing the cover, as she has done for the previous two editions. Finally, I am, as usual in these projects, grateful to a patient and supportive family, and particularly to my daughter, Amanda, who assisted in preparing the manuscript.

**John A. Buck**

*Marietta, Georgia*

*December, 2010*

On the cover: Radiated intensity patterns for a dipole antenna, showing the cases for which the wavelength is equal to the overall antenna length (red), two-thirds the antenna length (green), and one-half the antenna length (blue).

Quantity	Value
Electron charge	$e = (1.602\,177\,33 \pm 0.000\,000\,46) \times 10^{-19} \text{ C}$
Electron mass	$m = (9.109\,389\,7 \pm 0.000\,005\,4) \times 10^{-31} \text{ kg}$
Permittivity of free space	$\epsilon_0 = 8.854\,187\,817 \times 10^{-12} \text{ F/m}$
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$
Velocity of light	$c = 2.997\,924\,58 \times 10^8 \text{ m/s}$

Dielectric Constant ( $\epsilon'_r$ ) and Loss Tangent ( $\epsilon''/\epsilon'$ )

Material	$\epsilon'_r$	$\epsilon''/\epsilon'$
Air	1.0005	
Alcohol, ethyl	25	0.1
Aluminum oxide	8.8	0.000 6
Amber	2.7	0.002
Bakelite	4.74	0.022
Barium titanate	1200	0.013
Carbon dioxide	1.001	
Ferrite (NiZn)	12.4	0.000 25
Germanium	16	
Glass	4–7	0.002
Ice	4.2	0.05
Mica	5.4	0.000 6
Neoprene	6.6	0.011
Nylon	3.5	0.02
Paper	3	0.008
Plexiglas	3.45	0.03
Polyethylene	2.26	0.000 2
Polypropylene	2.25	0.000 3
Polystyrene	2.56	0.000 05
Porcelain (dry process)	6	0.014
Pyranol	4.4	0.000 5
Pyrex glass	4	0.000 6
Quartz (fused)	3.8	0.000 75
Rubber	2.5–3	0.002
Silica or SiO <sub>2</sub> (fused)	3.8	0.000 75
Silicon	11.8	
Snow	3.3	0.5
Sodium chloride	5.9	0.000 1
Soil (dry)	2.8	0.05
Steatite	5.8	0.003
Styrofoam	1.03	0.000 1
Teflon	2.1	0.000 3
Titanium dioxide	100	0.001 5
Water (distilled)	80	0.04
Water (sea)		4
Water (dehydrated)	1	0
Wood (dry)	1.5–4	0.01

Conductivity ( $\sigma$ )

Material	$\sigma$ , S/m	Material	$\sigma$ , S/m
Silver	$6.17 \times 10^7$	Nichrome	$0.1 \times 10^7$
Copper	$5.80 \times 10^7$	Graphite	$7 \times 10^4$
Gold	$4.10 \times 10^7$	Silicon	2300
Aluminum	$3.82 \times 10^7$	Ferrite (typical)	100
Tungsten	$1.82 \times 10^7$	Water (sea)	5
Zinc	$1.67 \times 10^7$	Limestone	$10^{-2}$
Brass	$1.5 \times 10^7$	Clay	$5 \times 10^{-3}$
Nickel	$1.45 \times 10^7$	Water (fresh)	$10^{-3}$
Iron	$1.03 \times 10^7$	Water (distilled)	$10^{-4}$
Phosphor bronze	$1 \times 10^7$	Soil (sandy)	$10^{-5}$
Solder	$0.7 \times 10^7$	Granite	$10^{-6}$
Carbon steel	$0.6 \times 10^7$	Marble	$10^{-8}$
German silver	$0.3 \times 10^7$	Bakelite	$10^{-9}$
Manganin	$0.227 \times 10^7$	Porcelain (dry process)	$10^{-10}$
Constantan	$0.226 \times 10^7$	Diamond	$2 \times 10^{-13}$
Germanium	$0.22 \times 10^7$	Polystyrene	$10^{-16}$
Stainless steel	$0.11 \times 10^7$	Quartz	$10^{-17}$

Relative Permeability ( $\mu_r$ )

Material	$\mu_r$	Material	$\mu_r$
Bismuth	0.999 998 6	Powdered iron	100
Paraffin	0.999 999 42	Machine steel	300
Wood	0.999 999 5	Ferrite (typical)	1000
Silver	0.999 999 81	Permalloy 45	2500
Aluminum	1.000 000 65	Transformer iron	3000
Beryllium	1.000 000 79	Silicon iron	3500
Nickel chloride	1.000 04	Iron (pure)	4000
Manganese sulfate	1.000 1	Mumetal	20 000
Nickel	50	Sendust	30 000
Cast iron	60	Supermalloy	100 000
Cobalt	60		

# DIVERGENCE

---

**RECTANGULAR**  $\nabla \cdot \mathbf{D} = \frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z}$

**CYLINDRICAL**  $\nabla \cdot \mathbf{D} = \frac{1}{\rho} \frac{\partial}{\partial \rho} (\rho D_\rho) + \frac{1}{\rho} \frac{\partial D_\phi}{\partial \phi} + \frac{\partial D_z}{\partial z}$

**SPHERICAL**  $\nabla \cdot \mathbf{D} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 D_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (D_\theta \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial D_\phi}{\partial \phi}$

# GRADIENT

---

**RECTANGULAR**  $\nabla V = \frac{\partial V}{\partial x} \mathbf{a}_x + \frac{\partial V}{\partial y} \mathbf{a}_y + \frac{\partial V}{\partial z} \mathbf{a}_z$

**CYLINDRICAL**  $\nabla V = \frac{\partial V}{\partial \rho} \mathbf{a}_\rho + \frac{1}{\rho} \frac{\partial V}{\partial \phi} \mathbf{a}_\phi + \frac{\partial V}{\partial z} \mathbf{a}_z$

**SPHERICAL**  $\nabla V = \frac{\partial V}{\partial r} \mathbf{a}_r + \frac{1}{r} \frac{\partial V}{\partial \theta} \mathbf{a}_\theta + \frac{1}{r \sin \theta} \frac{\partial V}{\partial \phi} \mathbf{a}_\phi$

## CURL

---

**RECTANGULAR**  $\nabla \times \mathbf{H} = \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) \mathbf{a}_x + \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \right) \mathbf{a}_y + \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right) \mathbf{a}_z$

**CYLINDRICAL**  $\nabla \times \mathbf{H} = \left( \frac{1}{\rho} \frac{\partial H_z}{\partial \phi} - \frac{\partial H_\phi}{\partial z} \right) \mathbf{a}_\rho + \left( \frac{\partial H_\rho}{\partial z} - \frac{\partial H_z}{\partial \rho} \right) \mathbf{a}_\phi$   
 $+ \frac{1}{\rho} \left[ \frac{\partial(\rho H_\phi)}{\partial \rho} - \frac{\partial H_\rho}{\partial \phi} \right] \mathbf{a}_z$

**SPHERICAL**  $\nabla \times \mathbf{H} = \frac{1}{r \sin \theta} \left[ \frac{\partial(H_\phi \sin \theta)}{\partial \theta} - \frac{\partial H_\theta}{\partial \phi} \right] \mathbf{a}_r + \frac{1}{r} \left[ \frac{1}{\sin \theta} \frac{\partial H_r}{\partial \phi} - \frac{\partial(r H_\phi)}{\partial r} \right] \mathbf{a}_\theta$   
 $+ \frac{1}{r} \left[ \frac{\partial(r H_\theta)}{\partial r} - \frac{\partial H_r}{\partial \theta} \right] \mathbf{a}_\phi$

## LAPLACIAN

---

**RECTANGULAR**  $\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}$

**CYLINDRICAL**  $\nabla^2 V = \frac{1}{\rho} \frac{\partial}{\partial \rho} \left( \rho \frac{\partial V}{\partial \rho} \right) + \frac{1}{\rho^2} \frac{\partial^2 V}{\partial \phi^2} + \frac{\partial^2 V}{\partial z^2}$

**SPHERICAL**  $\nabla^2 V = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial V}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 V}{\partial \phi^2}$

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