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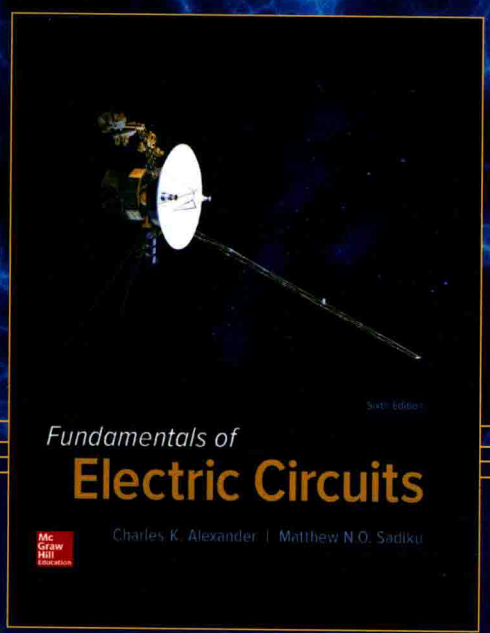
国外电子与电气工程技术丛书

电路基础

（英文版第6版·精编版）

[美] 查尔斯 K. 亚历山大（Charles K. Alexander）
马修 N. O. 萨迪库（Matthew N. O. Sadiku）著

Fundamentals of Electric Circuits
Sixth Edition



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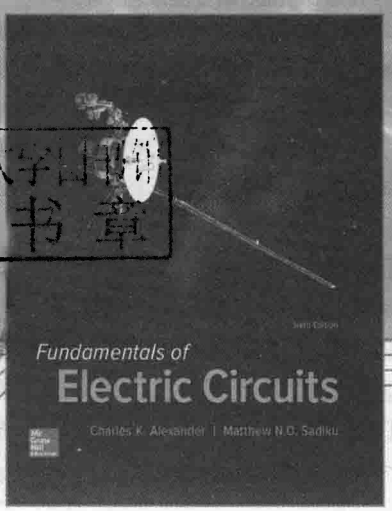

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出版者的话

文艺复兴以来，源远流长的科学精神和逐步形成的学术规范，使西方国家在自然科学的各个领域取得了垄断性的优势；也正是这样的传统，使美国在信息技术发展的六十多年间名家辈出、独领风骚。在商业化的进程中，美国的产业界与教育界越来越紧密地结合，信息学科中的许多泰山北斗同时身处科研和教学的最前线，由此而产生的经典科学著作，不仅擘划了研究的范畴，还揭示了学术的源变，既遵循学术规范，又自有学者个性，其价值并不会因年月的流逝而减退。

近年，在全球信息化大潮的推动下，我国的信息产业发展迅猛，对专业人才的需求日益迫切。这对我国教育界和出版界都既是机遇，也是挑战；而专业教材的建设在教育战略上显得举足轻重。在我国信息技术发展时间较短的现状下，美国等发达国家在其信息科学发展的几十年间积淀和发展的经典教材仍有许多值得借鉴之处。因此，引进一批国外优秀教材将对我国教育事业的发展起到积极的推动作用，也是与世界接轨、建设真正的世界一流大学的必由之路。

机械工业出版社华章公司较早意识到“出版要为教育服务”。自 1998 年开始，我们就将工作重点放在了遴选、移译国外优秀教材上。经过多年的不懈努力，我们与 Pearson、McGraw-Hill、Elsevier、John Wiley & Sons、CRC、Springer 等世界著名出版公司建立了良好的合作关系，从他们现有的数百种教材中甄选出 Alan V. Oppenheim、Thomas L. Floyd、Charles K. Alexander、Behzad Razavi、John G. Proakis、Stephen Brown、Allan R. Hambley、Albert Malvino、Peter Wilson、H. Vincent Poor、Hassan K. Khalil、Gene F. Franklin、Rex Miller 等大师名家的经典教材，以“国外电子与电气技术丛书”和“国外工业控制与智能制造丛书”为系列出版，供读者学习、研究及珍藏。这些书籍在读者中树立了良好的口碑，并被许多高校采用为正式教材和参考书籍。其影印版“经典原版书库”作为姊妹篇也越来越多被实施双语教学的学校所采用。

权威的作者、经典的教材、一流的译者、严格的审校、精细的编辑，这些因素使我们的图书有了质量的保证。随着电气与电子信息学科、自动化、人工智能等建设的不断完善和教材改革的逐渐深化，教育界对国外电气与电子信息类、控制类、智能制造类等相关教材的需求和应用都将步入一个新的阶段，我们的目标是尽善尽美，而反馈的意见正是我们达到这一终极目标的重要帮助。华章公司欢迎老师和读者对我们的工作提出建议或给予指正，我们的联系方法如下：

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Preface

In keeping with our focus on space for covers for our book, we have chosen the NASA Voyager spacecraft for the sixth edition. The reason for this is that like any spacecraft there are many circuits that play critical roles in their functionality. The beginning of the Voyager 1 and 2 odyssey began on August 20, 1977, for Voyager 2 and on September 5, 1977, for Voyager 1. Both were launched from NASA's Kennedy Space Center in Florida. The Voyager 1 was launched on a faster orbit so it eventually became the first man-made object to leave our solar system. There is some debate over whether it has actually left the solar system, but it certainly will at some point in time. Voyager 2 and two Pioneer spacecraft will also leave the solar system at some point in time.

Voyager 1 is still functioning and sending back data, a truly significant achievement for NASA engineers. The design processes that make the Voyager operate so reliably are based on the fundamentals discussed in this textbook. Finally, space is vast so that Voyager 1 will fly past other solar systems; the odds of actually coming into contact with something are so remote that it may virtually fly through the universe forever! For more about Voyager 1, go to NASA's website: www.nasa.gov/.

Features

New to This Edition

We have added learning objectives to each chapter to reflect what we believe are the most important items to learn from each chapter. These should help you focus more carefully on what you should be learning.

There are many revised end-of-chapter problems, new end-of-chapter problems, and revised practice problems. We continue to try and make our problems as practical as possible.

In addition, we have improved Connect for this edition by increasing the number of problems available substantially. Now, professors may select from more than a thousand problems as they build thier online homework assignments.

We have also built SmartBook for this edition. With SmartBook, students get the same text as the print version, along with personalized tips on what to study next, thanks to SmartBook's adaptive technology.

Retained from Previous Editions

A course in circuit analysis is perhaps the first exposure students have to electrical engineering. This is also a place where we can enhance some of the skills that they will later need as they learn how to design. An important part of this book is many ***design a problem*** problems. These problems were developed to enhance skills that are an important part of the design process. We know it is not possible to fully develop a student's design skills in a fundamental course like circuits. To fully develop design skills a student needs a design experience

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normally reserved for their senior year. This does not mean that some of those skills cannot be developed and exercised in a circuits course. The text already included open-ended questions that help students use creativity, which is an important part of learning how to design. We already have some questions that are open-ended but we desired to add much more into our text in this important area and have developed an approach to do just that. When we develop problems for the student to solve our goal is that in solving the problem the student learns more about the theory and the problem solving process. Why not have the students design problems like we do? That is exactly what we do in each chapter. Within the normal problem set, we have a set of problems where we ask the student to design a problem to help other students better understand an important concept. This has two very important results. The first will be a better understanding of the basic theory and the second will be the enhancement of some of the student's basic design skills. We are making effective use of the principle of learning by teaching. Essentially we all learn better when we teach a subject. Designing effective problems is a key part of the teaching process. Students should also be encouraged to develop problems, when appropriate, which have nice numbers and do not necessarily overemphasize complicated mathematical manipulations.

A very important advantage to our textbook, we have many Examples, Practice Problems, Review Questions, and End-of-Chapter Problems! Answers are provided for all practice problems and the odd numbered end-of-chapter problems.

The main objective of the sixth edition of this book remains the same as the previous editions—to present circuit analysis in a manner that is clearer, more interesting, and easier to understand than other circuit textbooks, and to assist the student in beginning to see the "fun" in engineering. This objective is achieved in the following ways:

- **Chapter Openers and Summaries**
  Each chapter opens with a discussion about how to enhance skills which contribute to successful problem solving as well as successful careers or a career-oriented talk on a subdiscipline of electrical engineering. This is followed by an introduction that links the chapter with the previous chapters and states the chapter objectives. The chapter ends with a summary of key points and formulas.
- **Problem-Solving Methodology**
  Chapter 1 introduces a six-step method for solving circuit problems which is used consistently throughout the book and media supplements to promote best-practice problem-solving procedures.
- **Student-Friendly Writing Style**
  All principles are presented in a lucid, logical, step-by-step manner. As much as possible, we avoid wordiness and giving too much detail that could hide concepts and impede overall understanding of the material.
- **Boxed Formulas and Key Terms**
  Important formulas are boxed as a means of helping students sort out what is essential from what is not. Also, to ensure that students clearly understand the key elements of the subject matter, key terms are defined and highlighted.

- **Margin Notes**
  Marginal notes are used as a pedagogical aid. They serve multiple uses such as hints, cross-references, more exposition, warnings, reminders not to make some particular common mistakes, and problem-solving insights.
- **Worked Examples**
  Thoroughly worked examples are liberally given at the end of every section. The examples are regarded as a part of the text and are clearly explained without asking the reader to fill in missing steps. Thoroughly worked examples give students a good understanding of the solution process and the confidence to solve problems themselves. Some of the problems are solved in two or three different ways to facilitate a substantial comprehension of the subject material as well as a comparison of different approaches.
- **Practice Problems**
  To give students practice opportunity, each illustrative example is immediately followed by a practice problem with the answer. The student can follow the example step-by-step to aid in the solution of the practice problem without flipping pages or looking at the end of the book for answers. The practice problem is also intended to test a student's understanding of the preceding example. It will reinforce their grasp of the material before the student can move on to the next section. Complete solutions to the practice problems are available to students on the website.
- **Design a Problem Problems**
  Finally, *design a problem* problems are meant to help the student develop skills that will be needed in the design process.
- **Historical Tidbits**
  Historical sketches throughout the text provide profiles of important pioneers and events relevant to the study of electrical engineering.
- **Early Op Amp Discussion**
  The operational amplifier (op amp) as a basic element is introduced early in the text.
- **Four-Color Art Program**
  An interior design and four-color art program bring circuit drawings to life and enhance key pedagogical elements throughout the text.
- **Extended Examples**
  Examples worked in detail according to the six-step problem solving method provide a road map for students to solve problems in a consistent fashion. At least one example in each chapter is developed in this manner.
- **EC 2000 Chapter Openers**
  Based on ABET's skill-based CRITERION 3, these chapter openers are devoted to discussions as to how students can acquire the skills that will lead to a significantly enhanced career as an engineer. Because these skills are so very important to the student while still in college as well after graduation, we use the heading, "*Enhancing your Skills and your Career.*"
- **Homework Problems**
  There are many new or revised end-of-chapter problems and changed practice problems which will provide students with plenty of practice

as well as reinforce key concepts.

- **Homework Problem Icons**
  Icons are used to highlight problems that relate to engineering design as well as problems that can be solved using *PSpice, Multisim, KCIDE,* or *MATLAB.*

Organization

This book was written for a two-semester or three-quarter course in linear circuit analysis. The book may also be used for a one-semester course by a proper selection of chapters and sections by the instructor. It is broadly divided into three parts.

- Part 1, consisting of Chapters 1 to 8, is devoted to dc circuits. It covers the fundamental laws and theorems, circuits techniques, and passive and active elements.
- Part 2, which contains Chapter 9 to 14, deals with ac circuits. It introduces phasors, sinusoidal steady-state analysis, ac power, rms values, three-phase systems, and frequency response.

The material in the three parts is more than sufficient for a two-semester course, so the instructor must select which chapters or sections to cover. Sections marked with the dagger sign (†) may be skipped, explained briefly, or assigned as homework. They can be omitted without loss of continuity. Each chapter has plenty of problems grouped according to the sections of the related material and diverse enough that the instructor can choose some as examples and assign some as homework. As stated earlier, we are using three icons with this edition. We are using to denote problems that either require *PSpice* in the solution process, where the circuit complexity is such that *PSpice* or *Multisim* would make the solution process easier, and where *PSpice* or *Multisim* makes a good check to see if the problem has been solved correctly. We are using to denote problems where *MATLAB* is required in the solution process, where *MATLAB* makes sense because of the problem makeup and its complexity, and where *MATLAB* makes a good check to see if the problem has been solved correctly. Finally, we use to identify problems that help the student develop skills that are needed for engineering design. More difficult problems are marked with an asterisk (*).

Comprehensive problems follow the end-of-chapter problems. They are mostly applications problems that require skills learned from that particular chapter.

Prerequisites

As with most introductory circuit courses, the main prerequisites, for a course using this textbook, are physics and calculus. Although familiarity with complex numbers is helpful in the later part of the book, it is not required. A very important asset of this text is that ALL the mathematical equations and fundamentals of physics needed by the student, are included in the text.

Acknowledgments

We would like to express our appreciation for the loving support we have received from our wives (Hannah and Kikelomo), daughters (Christina, Tamara, Jennifer, Motunrayo, Ann, and Joyce), son (Baixi), and our extended family members. We sincerely appreciate the invaluable help given us by Richard Rarick in helping us make the sixth edition a significantly more relevant book. He has checked all the new and revised problems and offered advice on making them more accurate and clear.

At McGraw-Hill, we would like to thank the following editorial and production staff: Raghu Srinivasan, global brand manager; Vincent Bradshaw, product developer; Nick McFadden, marketing manager; and Melissa Leick, content project manager.

The sixth edition has benefited greatly from the many outstanding individuals who have offered suggestions for improvements in both the text as well as the various problems. In particular, we thank Nicholas Reeder, Professor of Electronics Engineering Technology, Sinclair Community College, Dayton, Ohio, and Douglas De Boer, Professor of Engineering, Dordt College, Sioux Center, Iowa, for their detailed and careful corrections and suggestions for clarification which have contributed to making this a better edition. In addition, the following have made important contributions to this edition (in alphabetical order):

Zekeriya Aliyazicioglu, *California State Polytechnic University—Pomona*
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Salomon Oldak, *California State Polytechnic University—Pomona*
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Surendra Singh, *University of Tulsa*

Finally, we sincerely appreciate the feedback received from instructors and students who used the previous editions. We want this to continue, so please keep sending us e-mails or direct them to the publisher. We can be reached at c.alexander@ieee.org for Charles Alexander and sadiku@ieee.org for Matthew Sadiku.

C. K. Alexander and M. N. O. Sadiku

Supplements

Instructor and Student Resources

Available on Connect are a number of additional instructor and student resources to accompany the text. These include complete solutions for all practice and end-of-chapter problems, solutions in *PSpice* and *Multisim* problems, lecture PowerPoints®, and text image files. In addition, instructors can use COSMOS, a complete online solutions manual or-

ganization system to create custom homework, quizzes, and tests using end-of-chapter problems from the text.

Knowledge Capturing Integrated Design Environment for Circuits (*KCIDE for Circuits*)

This software, developed at Cleveland State University and funded by NASA, is designed to help the student work through a circuits problem in an organized manner using the six-step problem-solving methodology in the text. *KCIDE for Circuits* allows students to work a circuit problem in *PSpice* and *MATLAB*, track the evolution of their solution, and save a record of their process for future reference. In addition, the software automatically generates a Word document and/or a PowerPoint presentation. The software package can be downloaded for free.

It is hoped that the book and supplemental materials supply the instructor with all the pedagogical tools necessary to effectively present the material.

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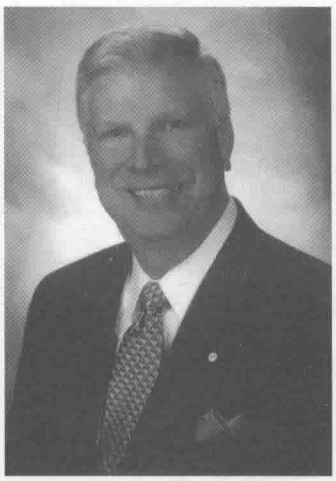
About the Authors



Charles K. Alexander

Charles K. Alexander is professor of electrical and computer engineering in the Washkewicz College of Engineering at Cleveland State University, Cleveland, Ohio. He is also the director of the Center for Research in Electronics and Aerospace Technology (CREATE). From 2002 until 2006 he was dean of the Fenn College of Engineering. He has held the position of dean of engineering at Cleveland State University, California State University, Northridge, and Temple University (acting dean for six years). He has held the position of department chair at Temple University and Tennessee Technological University as well as the position of Stocker Visiting Professor (an endowed chair) at Ohio University. He has held faculty status at all of the aforementioned universities.

Dr. Alexander has secured funding for two centers of research at Ohio University and Cleveland State University. He has been the director of three additional research centers at Temple and Tennessee Tech and has obtained research funding of approximately $100 million (in today's dollars). He has served as a consultant to 23 private and governmental organizations including the Air Force and the Navy.

He received the honorary Dr. Eng. from Ohio Northern University (2009), his PhD (1971) and M.S.E.E. (1967) from Ohio University, and the B.S.E.E. (1965) from Ohio Northern University.

Dr. Alexander has authored many publications, including a workbook and a videotape lecture series, and is coauthor of *Fundamentals of Electric Circuits*, currently in its fifth edition, *Engineering Skills for Career Success, Problem Solving Made* ALMOST *Easy*, the fifth edition of the *Standard Handbook of Electronic Engineering*, and *Applied Circuit Analysis*, all with McGraw-Hill. He has delivered more than 500 paper, professional, and technical presentations.

Dr. Alexander is a Life Fellow of the IEEE and served as its president and CEO in 1997. In addition he has held several volunteer positions within the IEEE during his more than 45 years of service. This includes serving from 1991 to 1999 on the IEEE board of directors.

He has received several local, regional, national, and international awards for teaching and research, including an honorary Doctor of Engineering degree, Fellow of the IEEE, the IEEE-USA Jim Watson Student Professional Awareness Achievement Award, the IEEE Undergraduate Teaching Award, the Distinguished Professor Award, the Distinguished Engineering Education Achievement Award, the Distinguished Engineering Education Leadership Award, the IEEE Centennial Medal, and the IEEE/RAB Innovation Award.

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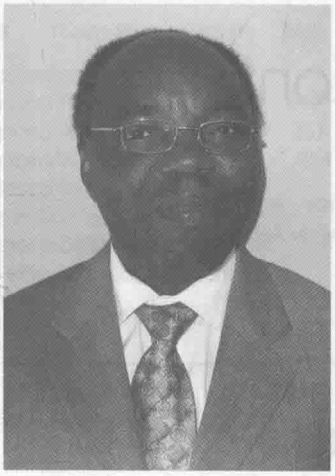
Matthew N. O. Sadiku received his PhD from Tennessee Technological University, Cookeville. From 1984 to 1988, he was an assistant professor at Florida Atlantic University, where he did graduate work in computer science. From 1988 to 2000, he was at Temple University, Philadelphia, Pennsylvania, where he became a full professor. From 2000 to 2002, he was with Lucent/Avaya, Holmdel, New Jersey, as a system engineer and with Boeing Satellite Systems as a senior scientist. He is currently a professor at Prairie View A&M University.

Dr. Sadiku is the author of more than 240 professional papers and over 60 books, including *Elements of Electromagnetics* (Oxford University Press, 6th ed., 2015), *Numerical Techniques in Electromagnetics with MATLAB* (CRC, 3rd ed., 2009), and *Metropolitan Area Networks* (CRC Press, 1995). Some of his books have been translated into French, Korean, Chinese (and Chinese Long Form in China Taiwan), Italian, Portuguese, and Spanish. He was the recipient of the 2000 McGraw-Hill/Jacob Millman Award for outstanding contributions in the field of electrical engineering. He was also the recipient of Regents Professor award for 2012 to 2013 by the Texas A&M University System.

His current research interests are in the areas of numerical modeling of electromagnetic systems and computer communication networks. He is a registered professional engineer and a fellow of the Institute of Electrical and Electronics Engineers (IEEE) "for contributions to computational electromagnetics and engineering education." He was the IEEE Region 2 Student Activities Committee Chairman. He was an associate editor for *IEEE Transactions on Education* and is a member of the Association for Computing Machinery (ACM).



Matthew N. O. Sadiku

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PART ONE

DC Circuits

OUTLINE

1 Basic Concepts
2 Basic Laws
3 Methods of Analysis
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6 Capacitors and Inductors
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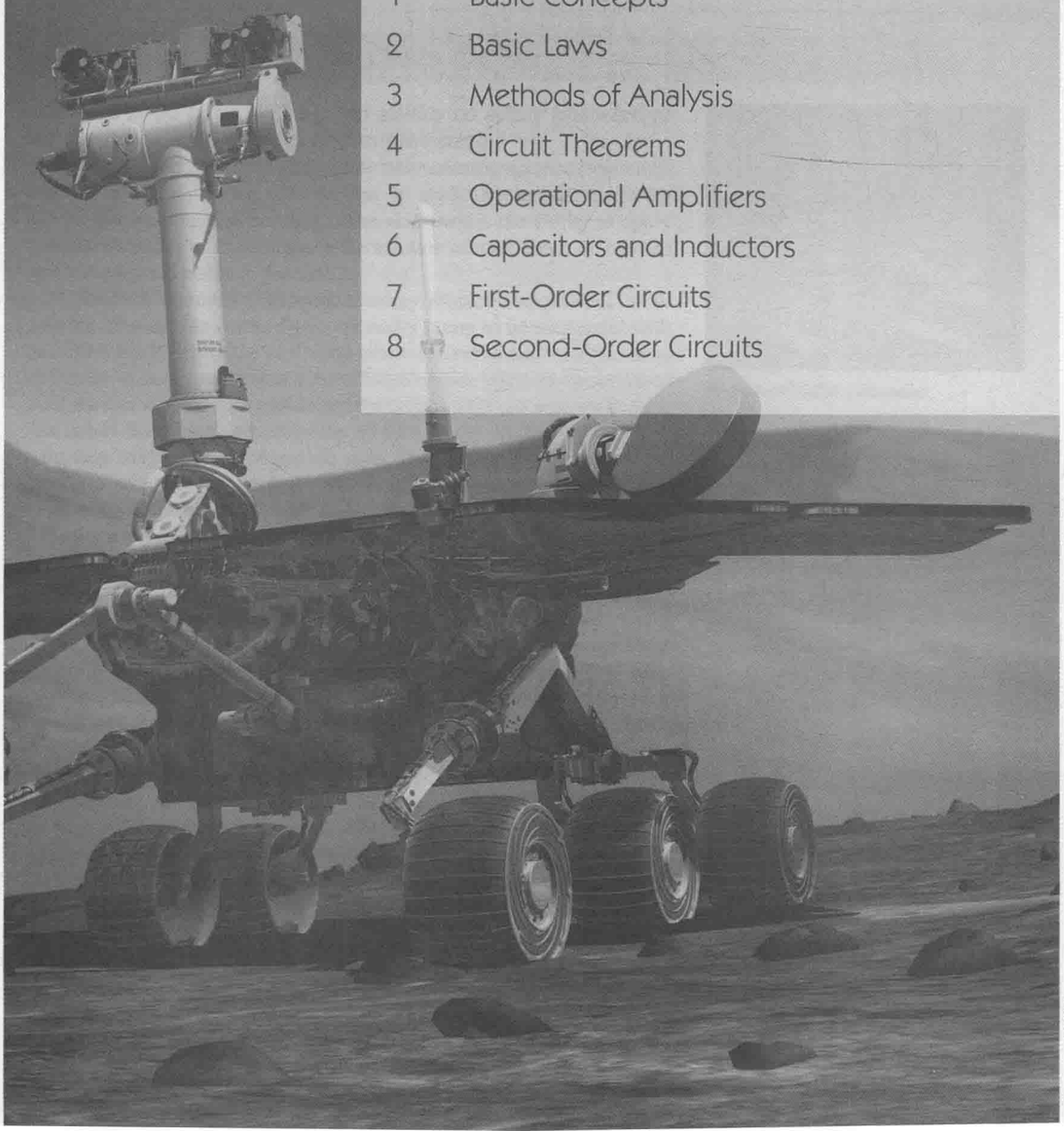

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PART ONE

chapter

1

Basic Concepts

Some books are to be tasted, others to be swallowed, and some few to be chewed and digested.

—Francis Bacon

Enhancing Your Skills and Your Career

ABET EC 2000 criteria (3.a), "*an ability to apply knowledge of mathematics, science, and engineering.*"

As students, you are required to study mathematics, science, and engineering with the purpose of being able to apply that knowledge to the solution of engineering problems. The skill here is the ability to apply the fundamentals of these areas in the solution of a problem. So how do you develop and enhance this skill?

The best approach is to work as many problems as possible in all of your courses. However, if you are really going to be successful with this, you must spend time analyzing where and when and why you have difficulty in easily arriving at successful solutions. You may be surprised to learn that most of your problem-solving problems are with mathematics rather than your understanding of theory. You may also learn that you start working the problem too soon. Taking time to think about the problem and how you should solve it will always save you time and frustration in the end.

What I have found that works best for me is to apply our six-step problem-solving technique. Then I carefully identify the areas where I have difficulty solving the problem. Many times, my actual deficiencies are in my understanding and ability to use correctly certain mathematical principles. I then return to my fundamental math texts and carefully review the appropriate sections, and in some cases, work some example problems in that text. This brings me to another important thing you should always do: Keep nearby all your basic mathematics, science, and engineering textbooks.

This process of continually looking up material you thought you had acquired in earlier courses may seem very tedious at first; however, as your skills develop and your knowledge increases, this process will become easier and easier. On a personal note, it is this very process that led me from being a much less than average student to someone who could earn a Ph.D. and become a successful researcher.

Photo by Charles Alexander

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