Fundamentals of

ELECTRIC CIRCUITS

Seventh Edition

Charles Alexander
Matthew Sadiku

Page i

seventh edition

Fundamentals of Electric Circuits

Charles K. Alexander

Professor Emeritus of Electrical Engineering and Computer Science

Cleveland State University

Matthew N. O. Sadiku

Department of Electrical and Computer Engineering

Prairie View A&M University

FUNDAMENTALS OF ELECTRIC CIRCUITS, SEVENTH EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 24 23 22 21 20 19

ISBN 978-1-260-22640-9 (bound edition)

MHID 1-260-22640-9 (bound edition)

ISBN 978-1-260-47767-2 (loose-leaf edition)

MHID 1-260-47767-3 (loose-leaf edition)

Product Developer: *Tina Bower*

Marketing Manager: *Shannon O'Donnell*

Content Project Managers: *Samantha Donisi-Hamm, Jason Stauter*

Buyer: *Sandy Ludovissy*

Design: *Jessica Cuevas*

Content Licensing Specialist: *Beth Cray*

Cover Image: *NASA, ESA, and M. Livio and The Hubble 20th Anniversary Team (STScI)*

Compositor: *Aptara®, Inc.*

Library of Congress Cataloging-in-Publication Data

Names: Alexander, Charles K., author. | Sadiku, Matthew N. O., author.

Title: Fundamentals of electric circuits / Charles K. Alexander, Department of Electrical and Computer Engineering, Cleveland State University,

Matthew N. O. Sadiku, Department of Electrical and Computer Engineering,

Prairie View A&M University.

Description: Seventh edition. | New York, NY : McGraw-Hill Education, [2021]

Identifiers: LCCN 2019018568| ISBN 9781260226409 (acid-free paper) | ISBN

1260226409 (acid-free paper)

Subjects: LCSH: Electric circuits.

Classification: LCC TK454 .A452 2021 | DDC 621.3815—dc23 LC record available at

https://lccn.loc.gov/2019018568

Page iii

Dedicated to our wives, Kikelomo and Hannah, whose understanding and support have truly made this book possible.

Matthew and Chuck

Contents

Page vi

Page vii

501-1111

Page xi

Preface

In keeping with our focus on space for the covers for our book, we have chosen a picture from the NASA Hubble Space Telescope for the seventh edition. The reason for this is that like any satellite, many electrical circuits play critical roles in their functionality..

Conceived in the 1940s as the Large Space Telescope, the Hubble Space Telescope became the most significant development in astronomy! Why was it needed? No matter how big and accurate a terrestrial telescope could be made, it would always be severely limited because of the earth's atmosphere. Building a telescope to operate above the atmosphere would open up the things that could be seen to essentially the whole universe. Finally, we can see deeper into space than ever before. After decades of research and planning, the Hubble Space Telescope was finally launched into space on April 24, 1990.

This incredible telescope has expanded the field of astronomy and our knowledge of the universe well beyond our very limited knowledge prior to its launch. It led to determining the age of the universe, a much better understanding of our own solar system, as well as our being able to peer into the deepest recesses of the universe.

Our cover is a Hubble picture of the "Pillars of Creation!" It is a picture taken deep within the galaxy and is of the Carina Nebula. Rising from the wall of the nebula, dust and towers of cool hydrogen mix to create this beautiful and dramatic image!

For more about Hubble, go to NASA's website: www.nasa.gov/.

Features

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 our 121 ***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 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.Page xii

A very important advantage to our textbook, we have a total of 2,481 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 seventh 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.

- Learning Objectives

  Each chapter has learning objectives that reflect what we believe are the most important items to learn from that chapter. These should help you focus more carefully on what you should be learning.

- 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.Page xiii

- 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.

- Application Sections

  The last section in each chapter is devoted to practical application aspects of the concepts covered in the chapter. The material covered in the chapter is applied to at least one or two practical problems or devices. This helps students see how the concepts are applied to real-life situations.

- Review Questions

  Ten review questions in the form of multiple-choice objective items are provided at the end of each chapter with answers. The review questions are intended to cover the little "tricks" that the examples and end-of-chapter problems may not cover. They serve as a self test device and help students determine how well they have mastered the chapter.

- Computer Tools

  In recognition of the requirements by ABET® on integrating computer tools, the use of *PSpice, Multisim, MATLAB,* and developing design skills are encouraged in a student-friendly manner. *PSpice* is covered early on in the text so that students can become familiar and use it throughout the text. Tutorials on all of these are available on Connect. *MATLAB* is also introduced early in the book.

- Design a Problem Problems

  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.Page xiv

- Fourier and Laplace Transforms Coverage

  To ease the transition between the circuit course and signals and systems courses, Fourier and Laplace transforms are covered lucidly

and thoroughly. The chapters are developed in a manner that the interested instructor can go from solutions of first-order circuits to Chapter 15. This then allows a very natural progression from Laplace to Fourier to AC.

- 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 580 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. We continue to try to make the problems as practical as possible.

- 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,* 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.

- Part 3, consisting of Chapters 15 to 19, are devoted to advanced techniques for network analysis. It provides students with a solid introduction to the Laplace transform, Fourier series, Fourier transform, and two-port network analysis.

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.Page xv

1.  denotes 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.

2. ML denotes 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.

3. ed identifies problems that help the student develop skills that are needed for engineering design. (*) identifies more difficult problems.

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 a significantly more relevant book.

At McGraw-Hill, we would like to thank the following editorial and production staff: Suzy Bainbridge, executive brand manager; Tina Bower, product developer; Shannon O'Donnell, marketing manager; and Jason Stauter, content project manager.

This text 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 textbook (in alphabetical order):Page xvi

Zekeriya Aliyazicioglu, *California State Polytechnic University—Pomona*

Rajan Chandra, *California State Polytechnic University—Pomona*

Mohammad Haider, *University of Alabama—Birmingham*

John Heathcote, *Reedley College*

Peter LoPresti, *University of Tulsa*

Robert Norwood, *John Brown University*

Aaron Ohta, *University of Hawaii—Manoa*

Salomon Oldak, *California State Polytechnic University—Pomona*

Hesham Shaalan, *U.S. Merchant Marine Academy*

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.

Problem Solving Made *Almost* Easy, a companion workbook to *Fundamentals of Electric Circuits*, is available for students who wish to practice their problem-solving techniques. The workbook can be found at mhhe.com/alexander7e and contains a discussion of problem-solving strategies and 150 additional problems with complete solutions provided.

McGraw-Hill Create®

Craft your teaching resources to match the way you teach! With McGraw-Hill Create, http://create.mheducation.com, you can easily rearrange chapters, combine material from other content sources, and quickly upload content you have written like your course syllabus or teaching notes. Find the content you need in Create by searching through thousands of leading McGraw-Hill textbooks. Arrange your book to fit your teaching style. Create even allows you to personalize your book's appearance by selecting the cover and adding your name, school, and course information. Order a Create book and you'll receive a complimentary print review copy in three to five business days or a complimentary electronic review copy (eComp) via e-mail in minutes. Go to http://create.mheducation.com today and register to experience how McGraw-Hill Create empowers you to teach *your* students *your* way.Page xvii

Page xix

Affordability & Outcomes = Academic Freedom!

You deserve choice, flexibility and control. You know what's best for your students and selecting the course materials that will help them succeed should be in your hands.

Thats why providing you with a wide range of options that lower costs and drive better outcomes is our highest priority.

Mc Graw Hill connect®

Students—study more efficiently, retain more and achieve better outcomes. Instructors—focus on what you love—teaching.

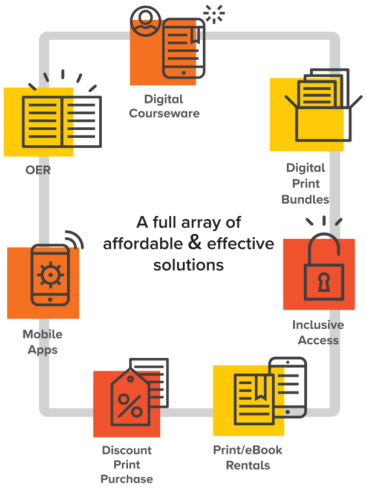
Laptop: McGraw-Hill Education

They'll thank you for it.

Study resources in Connect help your students be better prepared in less time. You can transform your class time from dull definitions to dynamic discussion. Hear from your peers about the benefits of Connect at **www.mheducation.com/highered/connect/smartbook**

Make it simple, make it affordable.

Connect makes it easy with seamless integration using any of the major Learning Management Systems—Blackboard®, Canvas, and D2L, among others—to let you organize your course in one convenient location. Give your students access to digital materials at a discount with our inclusive access program. Ask your McGraw-Hill representative for more information.



Learning for everyone.

McGraw-Hill works directly with Accessibility Services Departments and faculty to meet the learning needs of all students. Please contact your Accessibility Services office and ask them to email accessibility@mheducation.com, or visit **www.mheducation.com/about/accessibility.html** for more information.

Learn more at: www.mheducation.com/realvalue

Rent It

Affordable print and digital rental options through our partnerships with leading textbook distributors including Amazon, Barnes & Noble, Chegg, Follett, and more.

Go Digital

A full and flexible range of affordable digital solutions ranging from Connect, ALEKS, inclusive access, mobile apps, OER and more.

Get Print

Students who purchase digital materials can get a loose-leaf print version at a significantly reduced rate to meet their individual preferences and budget.

Page xx

A Note to the Student

This may be your first course in electrical engineering. Although electrical engineering is an exciting and challenging discipline, the course may intimidate you. This book was written to prevent that. A good textbook and a good professor are an advantage—but you are the one who does the learning. If you keep the following ideas in mind, you will do very well in this course.

- This course is the foundation on which most other courses in the electrical engineering curriculum rest. For this reason, put in as much effort as you can. Study the course regularly.

- Problem solving is an essential part of the learning process. Solve as many problems as you can. Begin by solving the practice problem following each example, and then proceed to the end-of-chapter problems. The best way to learn is to solve a lot of problems. An asterisk in front of a problem indicates a challenging problem.

- *Spice and Multisim,* computer circuit analysis programs, are used throughout the textbook. *PSpice,* the personal computer version of *Spice,* is the popular standard circuit analysis program at most universities. *PSpice for Windows* and *Multisim* are described on our website. Make an effort to learn *PSpice* and/or *Multisim,* because you can check any circuit problem with them and be sure you are handing in a correct problem solution.

- *MATLAB* is another software that is very useful in circuit analysis and other courses you will be taking. A brief tutorial on *MATLAB* can be found on our website. The best way to learn *MATLAB* is to start working with it once you know a few commands.

- Each chapter ends with a section on how the material covered in the chapter can be applied to real-life situations. The concepts in this section may be new and advanced to you. No doubt, you will learn more of the details in other courses. We are mainly interested in gaining a general familiarity with these ideas.

- Attempt the review questions at the end of each chapter. They will help you discover some "tricks" not revealed in class or in the textbook.

- Clearly a lot of effort has gone into making the technical details in this book easy to understand. It also contains all the mathematics and physics necessary to understand the theory and will be very useful in your other engineering courses. However, we have also focused on creating a reference for you to use both in school as well as when working in industry or seeking a graduate degree.Page xxi

- It is very tempting to sell your book after you have completed your classroom experience; however, our advice to you is *DO NOT SELL YOUR ENGINEERING BOOKS!* Books have always been expensive; however, the cost of this book is virtually the same as I paid for my circuits text back in the early 60s in terms of real dollars. In fact, it is actually cheaper. In addition, engineering books of the past are nowhere near as complete as what is available now.

When I was a student, I did not sell any of my engineering textbooks and was very glad I did not! I found that I needed most of them throughout my career.

A short review on finding determinants is covered in Appendix A, complex numbers in Appendix B, and mathematical formulas in Appendix C. Answers to odd-numbered problems are given in Appendix D.

Have fun!

C. K. A. and M. N. O. S.

Page xxiii

About the Authors

Charles K. Alexander

Charles K. Alexander Professor Emeritus of Electrical Engineering and Computer Science in the Washkewicz College of Engineering, Cleveland State University, Cleveland, Ohio. He was a Professor of Electrical Engineering and Computer Science at Cleveland State University from 2002 until 2018. He was the director of The Center for Research in Electronics and Aerospace Technology (CREATE) from 2004 until 2018. 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. He has held the position of Stocker Visiting Professor (an endowed chair) at Ohio University. He has held faculty status at all of the before mentioned named universities.

He has secured funding for the establishment of two centers of research, one in power and energy at Tennessee Technological University and another in sensor systems at Cleveland State University. He has been the director of three additional research centers at Temple and at Ohio University. He has obtained research funding of approximately $100 million (in today's dollars). He has served as a consultant to twenty-three private and governmental organizations, including the Air Force and the Navy.

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

He has authored many publications, including a workbook and a videotape lecture series, and is coauthor of *Fundamentals of Electric Circuits* (now in the seventh 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 authored or coauthored 30 books counting separate editions and foreign translations and he has made more than 500 paper, professional, and technical presentations. This circuits textbook was ranked number one or number two worldwide recently.

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

He has received several local, regional, national, and international awards for teaching, research, and service, 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 IEEE/RAB Innovation Award.Page xxiv

Matthew N. O. Sadiku

Matthew N. O. Sadiku received his B.Sc. degree in 1978 from Ahmadu Bello University, Zaria, Nigeria and his M.Sc. and Ph.D. degrees from Tennessee Technological University, Cookeville, TN, in 1982 and 1984, respectively. From 1984 to 1988, he was an assistant professor at Florida Atlantic University, Boca Raton, FL, where he did graduate work in computer science. From 1988 to 2000, he was at Temple University, Philadelphia, PA, where he became a full professor. From 2000 to 2002, he was with Lucent/Avaya, Holmdel, NJ, as a system engineer and with Boeing Satellite Systems, Los Angeles, CA, as a senior scientist. He is presently a professor of electrical and computer engineering at Prairie View A&M University, Prairie View, TX.

He is the author of over 660 professional papers and over 80 books including "Elements of Electromagnetics" (Oxford University Press, 7th ed., 2018), *Fundamentals of Electric Circuits* (McGraw-Hill, now in 7th edition, with C. Alexander), *Computational Electromagnetics with MATLAB* (CRC, 4th ed., 2019), and *Principles of Modern Communication Systems* (Cambridge University Press, 2017, with S. O. Agbo). In addition to the engineering books, he has written Christian books including *Secrets of Successful Marriages*, *How to Discover God's Will for Your Life*, and commentaries on all the books of the New Testament Bible. Some of his books have been translated into French, Korean, Chinese (and Chinese Long Form in 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 2012–2013 by the Texas A&M University System. 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. He is also a member of Association for Computing Machinery (ACM) and American Society of Engineering Education (ASEE). His current research interests are in the areas of computational electromagnetics, computer networks, and engineering education. His works can be found in his autobiography, *My Life and Work*

(Trafford Publishing, 2017) or his website: www.matthew-sadiku.com. He currently resides with his wife Kikelomo in Hockley, TX. He can be reached via email at sadiku@ieee.org.

Part One DC Circuits

Page 2

Source: NASA, ESA, and M. Livio and The Hubble 20th Anniversary Team (STScI)

OUTLINE

Page 3

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?

Charles Alexander

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