THE ANALYSIS AND DESIGN OF
LINEAR CIRCUITS

Eighth Edition

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WILEY

ELECTRIC QUANTITIES

Quantity	Symbol	Unit	Unit Abbreviation
Time	t	second	s
Frequency (cyclic)	f	hertz	Hz
Frequency (radian)	ω	radian/sec	rad/s
Phase angle	θ, ϕ	degree or radian	° or rad
Energy	w	joule	J
Power	p	watt	W
Charge	q	coulomb	C
Current	i	ampere	A
Electric field	$\mathscr{E}$	volt/meter	V/m
Voltage	v	volt	V
Impedence	Z	ohm	Ω
Admittance	Y	siemen	S
Resistance	R	ohm	Ω
Conductance	G	siemen	S
Reactance	X	ohm	Ω
Susceptance	B	siemen	S
Inductance, self	L	henry	H
Inductance, mutual	M	henry	H
Capacitance	C	farad	F
Magnetic flux	ϕ	weber	wb
Flux linkages	λ	weber-turns	wb-t
Power ratio	$\log_{10}(p_2/p_1)$	Bel	B

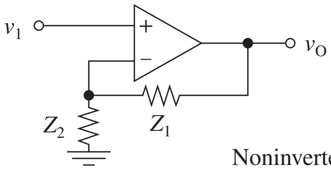
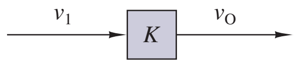
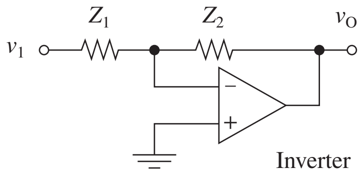
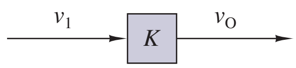
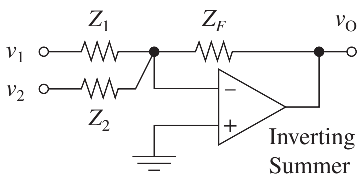
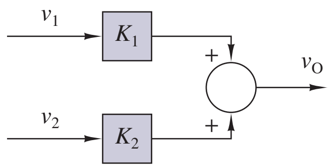
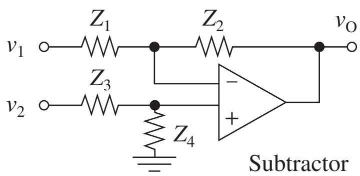
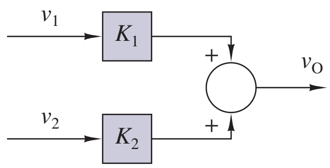
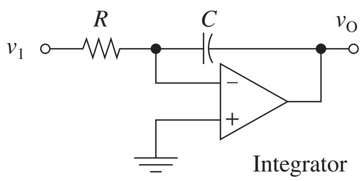
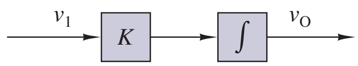
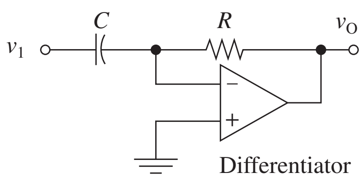
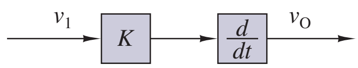
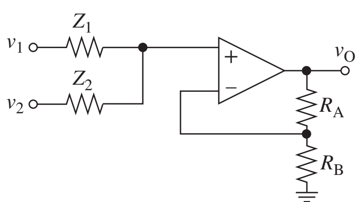
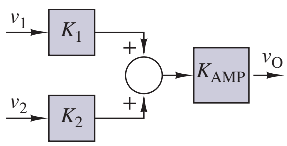
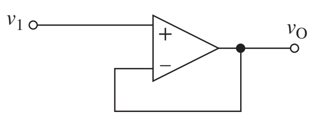
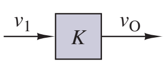
STANDARD DECIMAL PREFIXES

Multiplier	Prefix	Abbreviation	Multiplier	Prefix	Abbreviation
10^{18}	exa	E	10^{-2}	centi	c
10^{15}	peta	P	10^{-3}	milli	m
10^{12}	tera	T	10^{-6}	micro	μ
10^{9}	giga	G	10^{-9}	nano	n
10^{6}	mega	M	10^{-12}	pico	p
10^{3}	kilo	k	10^{-15}	femto	f
10^{-1}	deci	d	10^{-18}	atto	a

FUNDAMENTAL RELATIONSHIPS

	i-v Relationships		Impendence		
				Phasor-Domain	*s*-Domain
Resistor	$v_R(t) = i_R(t)R = \frac{i_R(t)}{G}$	$i_R(t) = \frac{v_R(t)}{R} = v_R(t)G$	Z_R	R	R
Inductor	$v_L(t) = L\frac{di_L(t)}{dt}$	$i_L(t) = \frac{1}{L}\int_0^t v_L(x)dx + i_L(0)$	Z_L	$j\omega L$	Ls
Capacitor	$v_C(t) = \frac{1}{C}\int_0^t i_C(x)dx + v_C(0)$	$i_C(t) = C\frac{dv_C(t)}{dt}$	Z_C	$\frac{1}{j\omega C}$	$\frac{1}{Cs}$

BASIC OP AMP MODULES

Circuit	Block Diagram	Gains
 Noninverter		$K = \dfrac{Z_1 + Z_2}{Z_2}$
 Inverter		$K = -\dfrac{Z_2}{Z_1}$
 Inverting Summer		$K_1 = -\dfrac{Z_F}{Z_1}$ $K_2 = -\dfrac{Z_F}{Z_2}$
 Subtractor		$K_1 = -\dfrac{Z_2}{Z_1}$ $K_2 = \left(\dfrac{Z_1 + Z_2}{Z_1}\right)\left(\dfrac{Z_4}{Z_3 + Z_4}\right)$
 Integrator		$K = -\dfrac{1}{RC}$
 Differentiator		$K = -RC$
 Noninverting Summer		$K_1 = Z_2/(Z_1+Z_2)$ $K_2 = Z_1/(Z_1+Z_2)$ $K_{AMP} = (R_A+R_B)/R_B$
 Follower		$K=1$

The Analysis and Design of Linear Circuits

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To our wives
Juanita, Kathleen, and Tricia

PREFACE

What Is Different about This Text?

Our approach to the art of teaching circuits in our textbook differs from most others. We realize that electric circuits are intimately integrated into so much of our modern technology that many students from different disciplines need to learn about them. Studying circuits can be daunting, but interesting, practical, and rewarding. This can be true even for students who are not majoring in electrical or computer engineering. We believe that most students who pursue engineering studies wish to be creative and design things. Most circuits texts do not focus on this basic desire, rather spend their pages teaching why and how electric circuits work without affording the student an opportunity to put this learning into practice. The longer it takes students to try their hand in designing things, the more likely it is that they will become disillusioned and frustrated—perhaps even to the point of changing to a different major.

We have long believed that an early introduction to design and design evaluation raises the excitement level and greatly increases student interest in their chosen discipline. Over 50 years of combined teaching experience at the USAF Academy, the University of Denver, the University of Colorado at Denver, and the Air Force Institute of Technology, has only served to strengthen our belief. This new edition furthers this strategy by adding more design and evaluation examples, exercises, homework problems, and real-world applications. In addition, students today solve problems using computers, by hand, and with a calculator. Access to personal computers, laptops, notebook computers, and "smart" devices is nearly ubiquitous, and key software used in circuit analysis and design has become available for free or at very deep discounts for students. This edition of our text includes more software examples, exercises, and discussions geared to making the study of circuits more in line with the interests of today's students. Our text has always included software, but generally as an extension for solving circuits by hand. This edition continues our effort begun with the sixth edition by integrating software intimately into the solution of circuit problems whenever and wherever it really helps to solve the problems. It still recognizes that using software does not replace the intuition that engineers must develop to analyze, design, and make smart judgments about different working solutions or designs.

The eight edition of *The Analysis and Design of Linear Circuits* improves on the seventh edition and remains friendly to users who prefer a Laplace-Early approach championed in our first edition, or those favoring the more traditional Phasor-First approach to AC circuits. A later section discusses how to use this text to pursue either approach using three different focuses. In this edition, we have added more skill-level examples, exercises, and problems that can help develop the student's confidence in mastering the different objectives. The eight edition assumes that the same student prerequisites as past editions and continues to rely on students having access to personal computers—although computer access is not essential for using this textbook—we believe it improves and expands learning. This edition targets students of all engineering disciplines who need an introductory circuit analysis course of one or two terms. The eight edition continues the authors' combined commitment to providing a modern, different, and innovative approach to teaching analysis, design, and design evaluation of electric circuits.

CONTINUING FEATURES

OBJECTIVES

This text remains structured around a sequence of carefully defined cognitive learning objectives and related evaluation tools based on Bloom's Taxonomy of Educational Objectives. The initial learning objectives focus on enabling skills at the knowledge, comprehension, and application levels of the taxonomy that we call Chapter Learning Objectives. As students demonstrate mastery of these lower levels, they are introduced to higher level objectives involving analysis, synthesis (design), and evaluation. Each learning objective is explicitly stated in terms of expected student proficiency in the homework sections, and each is followed by at least 10 homework problems specifically designed to evaluate student mastery of the objective. This framework has been a standard feature of all eight editions of this book and has allowed us to maintain a consistent level of expected student performance over the years. We also list our objectives in the chapter openers to orient the student to the expected outcomes. These objectives make it easier to assess student learning and prepare for accreditation reviews. To fulfill ABET Criterion 3: *The program must have documented student outcomes that prepare graduates to attain the program educational objectives.* And to fulfill Criterion 4: *The program must regularly use appropriate, documented processes for assessing and evaluating the extent to which the student outcomes are being attained. The results of these evaluations must be systematically utilized as input for the continuous improvement of the program. Other available information may also be used to assist in the continuous improvement of the program.*

INTEGRATING PROBLEMS

Every homework section ends with several integrating problems that test mastery of concepts that cover several objectives. These more in-depth problems test whether the student not only has mastered individual objectives but also was able to integrate knowledge across several objectives.

CIRCUIT ANALYSIS AND DESIGN

Our experience convinces us that an interweaving of analysis and design topics reinforces a student's grasp of circuit analysis fundamentals. Early involvement in design provides motivation as students apply their newly acquired analysis tools to practical situations. Using computer simulation software to verify their designs gives students an early degree of confidence that they have actually created a design that meets stated specifications. Ideally, a supporting laboratory program where students actually build and test their designs provides the final confirmation that they can create useful products. Design efforts as described in this text are very useful in helping to meet ABET's design Criterion 3(c): *an ability to design a system, component, or* *process to meet desired needs*. We identify design examples, exercises, and homework problems with an icon D.

Design Evaluation

Realistic design problems do not have unique solutions, so it is natural for students to wonder if their design is a good one. Using smart judgment to compare alternative solutions is a fundamental trait of good engineering. The evaluation of alternative designs introduces students to real-world engineering practice. Our text includes judgment problems that ask students, for example, to evaluate an "off-the-shelf" design and ask if it could meet a specific need. In such problems, we ask the student "would you buy it?", or would you buy it if one change was allowed to be made to it? Including design and the evaluation of design in an introductory course helps to convince students that circuit courses are not simply vehicles for teaching routine skills, such as node-voltage and mesh-current analyses, but also a vehicle for learning and practicing engineering judgment. This edition offers continued coverage of design and evaluation among the worked examples, exercises, and homework problems. We use software extensively to help students visualize specifications, alternatives, and their design results. This, in turn, helps them to create better designs and make smart choices between competing designs. Evaluation generally involves the practical side of design and can support ABET Criterion 3(c)—specifically to create designs … *within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.* We identify evaluation examples, exercises, and homework problems with an icon E.

The OP AMP

A central feature of this text continues to be an early introduction and integrated treatment of the OP AMP. The modular form of OP AMP circuits simplifies analog circuit analysis and design by minimizing the effects of loading. This feature allows the interconnection of simple building blocks to produce complex signal processing functions that are especially useful to instrumentation and signal shaping applications. The close agreement between theory, simulation, and hardware allows students to analyze, design, and successfully build useful OP AMP circuits in the laboratory. The text covers numerous OP AMP applications, such as digital-to-analog conversion, transducer interface circuits, comparator circuits, block diagram realization, first-order filters, and multiple-pole active filters. These applications are especially useful to students from other engineering disciplines that require knowledge of instrumentation, interfacing, filtering, or signal processing.

Laplace Transforms

Laplace transforms are used to solve differential equations using algebraic techniques. In circuits, Laplace transforms are used to treat important concepts such as zero-state and zero-input responses, impulse and step responses, convolution, frequency response, and filter design. An important pedagogical question is where Laplace transforms should be taught—in the Circuits course, the Signals and Systems course, a Differential Equations course, or elsewhere? The traditional approach in circuits has been to first teach phasors and use them to study ac circuit analysis, steady-state ac power, polyphase circuit analysis, magnetically coupled circuits, and frequency response. This extended treatment of phasor analysis means that Laplace transforms are often delayed to the last weeks of the second semester and treated as an advanced topic along with Fourier methods and two-port networks.

Typically, then, Laplace transforms are taught in earnest in a Signals and Systems course, where their linkage to phasors is often overlooked. We have long advocated an early Laplace approach, one in which Laplace transforms are introduced and applied to circuit analysis *before* phasors are introduced. The advantage of treating Laplace-based circuit analysis first is that once mastered, it makes learning phasor-based analysis easier and more intuitive. Students quickly make the connection between phasor analysis and the concepts of network functions, transient response, and sinusoidal steady-state response developed through *s*-domain circuit analysis. We do not claim that Laplace analysis is more fundamental or even more important than phasor analysis. We do claim that the learning effort needed to master both phasor analysis and Laplace analysis is not a zero-sum game. Our experience is that less classroom time is needed to ensure mastery of both methods of analysis when Laplace transform analysis is treated before phasor analysis. Emphasizing transform methods in the circuit course also better prepares students to handle the profusion of transforms they will encounter in subsequent Signals and Systems courses.

SIGNALS AND SIGNAL PROCESSING

We begin our treatment of dynamic circuits with a separate chapter on waveforms and signal characteristics. This chapter gives students early familiarity with important input and output signals encountered in the study of linear circuits. Introducing signals at the beginning of dynamic circuit analysis lets students become comfortable with time-varying signals without having to simultaneously deal with applying them to circuits. A further emphasis on signal processing and systems is achieved through the use of block diagrams, input–output relationships, and transform methods. The ultimate goal is for students to understand that time-domain waveforms and frequency-domain transforms are simply alternative ways to characterize signals and signal processing with each domain approach providing different insight into the circuit's performance. Viewing signals in both domains naturally leads to discussions of important concepts such as signal bandwidth, signal sampling, and reciprocal spreading. It is also useful knowledge in choosing alternative design approaches to filters.

COMPUTER TOOLS

Our philosophy recognizes that today students come to the Circuits course being comfortable using a computer. Many already know how to use several computer tools such as spreadsheets and word processing. Some may be familiar with math solvers and possibly simulation software. One of our goals is to help them learn how to effectively use these tools. Knowing when to use these tools and how to interpret the results is essential to understanding circuits. We use three types of computer programs in this text to illustrate computer-aided circuit analysis, namely spreadsheets (Excel®), math solvers (MATLAB®), and circuit simulators (Multisim®). Beginning with Chapter 1, examples, exercises, and homework problems related to computer-aided circuit analysis are integrated into all chapters. The purpose of the examples is to show students how to develop a problem-solving style that includes the intelligent use of the productivity tools routinely used by practicing engineers. Exercises following most examples help students immediately practice the software skill demonstrated in the example. There are 32 examples and 53 exercises that use computer tools in their solution. There are 325 homework problems that require the use of a computer tool and all are identified by a computer icon .

We have created a Web Appendix D that includes additional examples that make use of software tools. This approach of integrating software tools into circuits directly supports ABET's Criterion 3(k)—*an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.*

APPLICATION EXAMPLES

The text has many examples that link directly to practical uses. The purpose of these examples is to show the student that the topics being covered are more than a pedagogical exercise. These real-world examples find use in common applications and products. We have increased to 44 the number of Application Examples. They include topics, such as cathode-ray tube (CRT) operation, batteries, source–load interfacing, bipolar junction transistor (BJT) operation, digital multimeters, common-mode rejection ratio (CMRR) in instrumentation amplifiers, attenuation pads, electrocardiograph (ECG), and clock-timing waveforms, three on how to obtain a waveform equation from an oscilloscope, sample-hold circuits, resonance, impedance bridge, gain-bandwidth product, digital filtering, frequency content of a full-wave rectifier, isolation- and auto-transformers, and more. These examples can be used to support ABET Criterion 3(j)—*a knowledge of contemporary issues.*

TEXT AND WEB APPENDICES

Since many students may need to review this material, we have included a text appendix on complex numbers. There are also five Web appendices: One on the solution of linear equations (A), one on Butterworth and Chebyshev poles (B), a new appendix on Fourier transforms (C), one on software tools (D), and one with all the Exercises worked out (E). These appendices are available at www.wiley.com/college/thomas.

NEW FEATURES OF THE EIGHT EDITION

SKILLS: BUILDING EXAMPLES, EXERCISES, AND PROBLEMS

Users have asked that we include additional easier, skills-building examples, exercises, and problems as a means of helping students build confidence. Throughout the text, but especially in the early chapters, we have added several one-concept examples and exercises to key sections. In addition, we added numerous such problems in support of each learning objective. These skill-building items are at the Bloom's Taxonomy "Comprehension" level, rather than the more advanced "Application" and "Analysis" levels. Solutions to Exercises are in a special Web Appendix E.

CIRCUIT DESIGN AND DESIGN EVALUATION

Our emphasis on creating solutions and choosing the better or best one has been strengthened with the inclusion of 64 design examples, 81 design exercises, and 263 design homework problems. There are dozens of design evaluation examples, exercises, and homework problems. In this edition, there are 21 evaluation examples, 16 evaluation exercises, and 79 homework problems that require applying judgment.

FREQUENCY RESPONSE AND ACTIVE FILTERS

We have continued to improve Chapter 12 on frequency response and Chapter 14 on active filters. These chapters are excellent means of understanding the frequency behavior of circuits. We have maintained our integration of software to assist the student in understanding frequency behavior through Bode diagrams and pole-zero diagrams in both chapters. Users have told us that Chapter 14 often proves useful to students in subsequent design courses where knowledge of active filters may be needed. As a result, we have sustained our coverage of active multipole notch and tuned filters. Both chapters have more design and evaluation examples as well as more homework problems.

AC Power Systems

In our chapter on three-phase AC power circuits, we have kept it in line with what today's students should know. We emphasized power flow and systems in both single phase and three phase. We added new simulation examples, exercises, and homework.

Two Ports

In response to several users, we have updated and moved the chapter on two ports (Chapter 17) from the main text to the Web. Although located on the Web, this chapter is fully integrated with the text, with examples, exercises, and problems. It has index references and answers to selected homework problems. We have added discussion, examples, and exercises to illustrate that two-port parameters are not just another way to find voltage and current responses. Rather, their primary utility is to determine global circuit properties such as voltage gain, current gain, feedback, and Thévenin equivalence. We have added simulation examples to this chapter.

Using This Edition for Laplace Early

The eight edition is designed so that it can be used as a Laplace Early version as well as a traditional Phasor First version. The phasor analysis chapter (Chapter 8) comes before the study of Laplace transform techniques (Chapters 9–11). Those wishing to follow the traditional approach can follow the eighth edition chapter organization through Chapter 8, on phasor analysis, with a possible delaying of Chapter 7 until the second semester. Those choosing a Laplace Early approach can follow the present chapter organization through Chapter 7, skip Chapter 8, and proceed directly to the Laplace chapters. The current edition includes an introduction to phasor analysis in Sect. 11–5, dealing with the sinusoidal steady state. As a result, Laplace Early users can study phasor analysis in Chapter 8 at any point after Chapter 11. The following table shows suggested chapter sequencing for the traditional and Laplace Early approaches for three different subject matter emphases. The second author used the Traditional–Electronics sequence at the USAF Academy and has used the Laplace Early–Systems sequence at the University of Denver. Enough material is available in the printed text and in the Web appendices to allow the construction of other topic sequences. Other organizational options are available in the Instructor Manual.

Emphasis	Semester 1							Semester 2						
Traditional (Phasor First)														
Power	1	2	3	4	5	6	8/7	7/8	15	16	9	10	11	12
Systems	1	2	3	4	5	6	8/7	7/8	9	10	11	12	13	14
Electronics	1	2	3	4	5	6	8/7	7/8	9	10	11	12	14	15/17
Laplace Early														
Power	1	2	3	4	5	6	7	9	10	11	12	8	15	16
Systems	1	2	3	4	5	6	7	9	10	11	12	13	14	8/15
Electronics	1	2	3	4	5	6	7	9	10	11	12	14	15	17

USE OF SOFTWARE IN THIS EDITION

Software use throughout the text has been significantly increased and strengthened to include many new MATLAB, Multisim, and Excel examples to help practice using the software. Although there are many simulation products that can be used, in this edition, we chose National Instrument's Multisim® because of its ease of use, low cost, breath of problems, the ability to insert virtual laboratory instruments in a circuit, and its easy integration with another NI product, LabView®. There is an expanded Web Appendix D to simplify students' use of software. There are 257 homework problems that suggest solutions using MATLAB, Multisim, or both.

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CONTENTS

CHAPTER 1 INTRODUCTION

The electromotive action manifests itself in the form of two effects which I believe must be distinguished from the beginning by a precise definition. I will call the first of these "electric tension," the second "electric current."

André-Marie Ampère, 1820,
French Mathematician/Physicist

Some History Behind This Chapter

André Ampère (1775–1836) was the first to recognize the importance of distinguishing between the electrical effects we now call voltage and current. He also invented the galvanometer, the forerunner of today's voltmeter and ammeter. A natural genius, he had mastered all the then-known mathematics by age 12. He is best known for defining the mathematical relationship between electric current and magnetism, now known as Ampère's law.

Why This Chapter Is Important Today

Welcome to the study of Linear Circuits. In this chapter you are introduced to the lexicon of electrical engineering. You will learn both the terminology and the variables that will be used throughout the book. Important concepts introduced here are voltage and current, the reference marks used to define them, and a voltage benchmark called ground. In addition, you will gain an initial appreciation of the value of the computational software that is common in the electrical engineering profession.

Chapter Sections

Chapter Learning Objectives

1-1 Electrical Symbols and Units (Sect. 1–2)

Given an electrical quantity described in terms of words, scientific notation, or decimal prefix notation, convert the quantity to an alternative description.

1-2 Circuit Variables (Sect. 1–3)

Given any two of the three signal variables (i, v, p) or the two basic variables (q, w), find the magnitude and direction (sign) of the unspecified variables.

1-3 Software Introductions (Sect. 1–4, Web Appendix D)

Given a simple computational problem, use MATLAB as an appropriate engineering tool to solve the problem. (We will introduce the use of Multisim to solve simulation problems starting in Chapter 2.)

1–1 About This Book

The basic purpose of this book is to introduce the analysis and design of linear circuits. Circuits are important in electrical engineering because they process electrical signals that carry energy and information. For the present we can define a **circuit** as an interconnection of electrical devices and a **signal** as a time-varying electrical entity. For example, the information stored on an optical disk is recovered in the optical disk player (e.g., Blu-Ray) as electronic signals, initially stored as discrete (digital) data that are processed by circuits to generate continuous (analog) audio and video outputs. In an electrical power system some form of stored energy (coal, nuclear, hydro, chemical, etc.) is converted to electrical form and transferred to loads, where the energy is converted into the form (mechanical, light, heat, etc.) required by the customer. The optical disk player and the electrical power system both involve circuits that process and transfer electrical signals carrying energy and information.

In this text we are primarily interested in **linear circuits**. An important feature of a linear circuit is that the amplitude of the output signal is proportional to the input signal amplitude. The proportionality property of linear circuits greatly simplifies the process of circuit analysis and design. Most circuits are linear only within a restricted range of signal levels. When driven outside this range they become nonlinear, and proportionality no longer applies. Although we will treat a few examples of nonlinear circuits, our attention is focused on circuits operating within their linear range.

Our study also deals with interface circuits. For the purposes of this book, we define an **interface** as a pair of accessible terminals at which signals may be observed or specified. The interface idea is particularly important with integrated circuit (IC) technology. Integrated circuits involve many thousands, indeed millions, of interconnections, but only a small number are accessible to the user. Designing systems using integrated circuits involves interconnecting complex circuits that have only a few accessible terminals. This often includes relatively simple circuits whose purpose is to change signal levels or formats. Such interface circuits are intentionally introduced to ensure that the appropriate signal conditions exist at the connections between complex integrated circuits.

Today's engineers analyze and design circuits using software tools. Using mathematical analysis tools such as MATLAB, MathCad, and Mathematica as well as circuit simulation tools such as National Instrument's NI Multisim (Electronic Workbench) and Cadence (OrCAD), engineers can improve their understanding and results. As you proceed through this text, we help you develop the software skills necessary to become practiced in linear circuit design. Although there are many different software programs that you can use effectively to develop these skills, we will concentrate on MATLAB and Multisim.

Course Objectives

This book is designed to help you develop the knowledge and application skills needed to solve three types of circuit problems: analysis, design, and evaluation. An **analysis** problem involves finding the output signals of a given circuit with known input signals. Circuit analysis is the foundation for understanding the interaction of signals and circuits. A **design** problem involves devising one or more circuits that perform a given signal-processing function. Usually there are several possible solutions to a design problem. This leads to an **evaluation** problem, which involves picking the best solution from among several candidates using factors such as cost, power consumption, and part counts. In real life the engineer's role is a blend of analysis, design, and evaluation, and in practice the boundaries between these categories are often blurred.

This text contains many worked examples to help you develop your problem-solving skills. The **examples** include a problem statement and provide the intermediate steps needed to obtain the final answer. The examples often treat analysis problems, although design and evaluation examples are included. This text also contains a number of **exercises** that include only the problem statement and the final answer. You should use the exercises to test your understanding of the circuit concepts discussed in the preceding section. Solutions to all Exercises are available on Web Appendix E.

Throughout we will show you where it is useful to turn to software to help solve problems, be they analysis, design, or evaluation. The computer icon identifies examples, exercises, and problems that are best solved using software tools.

CHAPTER OBJECTIVES

At the start of each chapter we provide three motivational aspects for what you are about to learn. First, we present a brief perspective of a key historical figure important to the content of the chapter. Second, we give an overview of why this chapter is important to your study. Third, we introduce you to the learning objectives for the chapter.

The **chapter learning objectives** are a carefully structured set of enabling skills. They are introduced in the chapter opener and repeated in more detail at the end of each chapter. Collectively, these objectives represent the basic knowledge and understanding needed to master the topics covered in each chapter. In the problems section the objectives explicitly state the expected behavior, followed by a graduated set of homework problems designed to help you assess your level of achievement. Each objective also lists worked examples and exercises in the text that help you work the related homework problems. Once you understand the chapter learning objectives, you can move on to the integrating problems at the very end of the problems section. These problems require mastery of several chapter learning objectives from the present and prior chapters and provide an opportunity to test your ability to deal with comprehensive, integrative problems. Throughout the text, when appropriate, we label the primary purpose of the example, exercise, course-learning problem, or chapter-integrating problem with the symbol A for analysis, D for design, or E for evaluation.

ASSESSMENT AND ACCREDITATION

Material in this text can be used effectively in a properly designed course to support ABET accreditation criteria associated with comprehension, use of modern tools, design, evaluation, and real-world constraints. Additional accreditation and assessment guidance is provided in the Instructors Manual.

1–2 SYMBOLS AND UNITS

Throughout this text we will use the international system (SI) of units. The SI system includes six fundamental units: meter (m), kilogram (kg), second (s), ampere (A), kelvin (K), and candela (cd). All the other units of measure can be derived from these six.

Like all disciplines, electrical engineering has its own terminology and symbology. The symbols used to represent some of the more important physical quantities and their units are listed in Table 1–1. It is not our purpose to define these quantities here or to offer this list as an item for memorization. Rather, the purpose of this table is merely to list in one place all the electrical quantities used in this book.

Numerical values in engineering range over many orders of magnitude. Consequently, the system of standard decimal prefixes in Table 1–2 is used. These prefixes on a unit abbreviation symbol indicate the power of 10 that is applied to the numerical value of the quantity.

TABLE 1–1 SOME IMPORTANT QUANTITIES, THEIR SYMBOLS, AND UNIT ABBREVIATIONS

Quantity	Symbol	Unit	Unit Abbreviation
Time	t	second	s
Frequency	f	hertz	Hz
Radian frequency	ω	radian/second	rad/s
Phase angle	θ, ϕ	degree or radian	° or rad
Energy	w	joule	J
Power	p	watt	W
Charge	q	coulomb	C
Current	i	ampere	A
Electric field	$\mathscr{E}$	volt/meter	V/m
Voltage	v	volt	V
Impedance	Z	ohm	Ω
Admittance	Y	siemens	S
Resistance	R	ohm	Ω
Conductance	G	siemens	S
Reactance	X	ohm	Ω
Susceptance	B	siemens	S
Inductance, self	L	henry	H
Inductance, mutual	M	henry	H
Capacitance	C	farad	F
Magnetic flux	ϕ	weber	wb
Flux linkages	λ	weber-turns	wb-t
Power ratio	PR_{dB}	bel	B

TABLE 1–2 STANDARD DECIMAL PREFIXES

Multiplier	Prefix	Abbreviation
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Exercise 1–1

Given the pattern in the statement 1 kΩ = 1 kilohm = 1×10^3 ohms, fill in the blanks in the following statements using the standard decimal prefixes.

(a) ____ = ____ = 5×10^{-3} watts
(b) 10.0 dB = ____ = ____
(c) 3.6 ps = ____ = ____
(d) ____ = 0.03 microfarads = ____
(e) ____ = ____ = 6.6×10^9 hertz

Answers:

(a) 5.0 mW = 5 milliwatts
(b) 10.0 decibels = 1.0 bel
(c) 3.6 picoseconds = 3.6×10^{-12} seconds
(d) 30 nF or 0.03 μF = 30.0×10^{-9} farads
(e) 6.6 GHz = 6.6 gigahertz

1–3 CIRCUIT VARIABLES

The underlying physical variables in the study of electronic systems are **charge** and **energy**. The idea of electrical charge explains the very strong electrical forces that occur in nature. To explain both attraction and repulsion, we say that there are two kinds of charge—positive and negative. Like charges repel, whereas unlike charges attract each other. The symbol q is used to represent charge. If the amount of charge is varying with time, we emphasize the fact by writing q as a function of t or $q(t)$. In the SI system, charge is measured in **coulombs** (abbreviated C). The smallest quantity of charge in nature is an electron's charge $\left(q_E = -1.6 \times 10^{-19}\text{ C}\right)$. Thus, there are $1/|q_E| = 6.25 \times 10^{18}$ electrons in 1 coulomb of charge.

Electrical charge is a rather cumbersome variable to measure in practice. Moreover, in most situations the charges are moving, so we find it more convenient to measure the amount of charge passing a given point per unit time. If $q(t)$ is the cumulative charge passing through a point, we define a signal variable i called **current** as follows:

$$i = \frac{dq}{dt} \tag{1–1}$$

Current is a measure of the flow of electrical charge. It is the time rate of change of charge passing a given point in a circuit. The physical dimensions of current are coulombs per second. In the SI system, the unit of current is the **ampere** (abbreviated A). That is,

$$1\text{ coulomb/second} = 1\text{ ampere} = 1\text{ A}$$

Since there are two types of electrical charge (positive and negative), there is a bookkeeping problem associated with the direction assigned to the current. In engineering it is customary to define the direction of current as the direction of the net flow of positive charge. Since electrons have negative charge, they move in the opposite direction of the current.

A second signal variable called **voltage** is related to the change in energy that would be experienced by a charge as it passes through a circuit. The symbol w is commonly used to represent energy. In the SI system of units, energy carries the units of **joules** (abbreviated J). If a small charge dq were to experience a change in energy dw in passing from point A to point B in a circuit, then the voltage v between A and B is defined as the change in energy per unit charge. We can express this definition in differential form as

$$v = \frac{dw}{dq} \tag{1–2}$$

Voltage does not depend on the path followed by the charge dq in moving from point A to point B. Furthermore, there can be a voltage between two points even if there is no charge motion, since voltage is a measure of how much energy dw would be involved if a charge dq was moved. The dimensions of voltage are joules per coulomb. The unit of voltage in the SI system is the **volt**[1] (abbreviated V). That is,

$$1 \text{ joule}/\text{coulomb} = 1 \text{ volt} = 1 \text{ V}$$

The general definition of the physical variable called **power** is the time rate of change of energy:

$$p = \frac{dw}{dt} \tag{1–3}$$

The dimensions of power are joules per second, which in the SI system is called a **watt**[2] (abbreviated W). In electrical circuits it is useful to relate the power associated with a device or element to the signal variables current and voltage. Using the chain rule, Eq. (1–3) can be written as

$$p = \left(\frac{dw}{dq}\right)\left(\frac{dq}{dt}\right) \tag{1–4}$$

Now using Eqs. (1–1) and (1–2), we obtain

$$p = vi \tag{1–5}$$

The electrical power associated with a situation is determined by the product of voltage and current. The total energy transferred during the period from t_1 to t_2 is found by solving for dw in Eq. (1–3) and then integrating

$$w_T = \int_{w_1}^{w_2} dw = \int_{t_1}^{t_2} p\,dt \tag{1–6}$$

In sum, the three key circuit variables—current, voltage, and power—are measured as follows: current at individual points, voltage always between two points, and power at an element or device.

APPLICATION EXAMPLE 1–1

For nearly a century, visual displays of alternating signals on televisions, oscilloscopes, radar screens, and so on were seen using a cathode ray tube or CRT. In Europe, it was called the Braun tube named after its German inventor Ferdinand Braun in 1897. However, it was J. J. Thomson, an English physicist, who was able to show how to deflect cathode rays, a fundamental function of the modern CRT. In its basic operation, an electron beam is produced from a heated filament connected to a negative voltage called the cathode. These energized electrons are then accelerated by a positive voltage, placed at a screen called the anode that is located some distance away inside an evacuated container, usually made of glass, called a vacuum tube. These electrons pass through the anode and strike a phosphorescent screen exciting the phosphor and producing light at the spot they strike. Another voltage placed across the neck of the CRT can cause the beam to be deflected in proportion

[1]The volt is named after the Italian physicist, Alessandro Volta (1745–1827), for the discovery of a practical source of current—the battery.

[2]The watt is named after the Scottish inventor and mechanical engineer, James Watt (1736–1819), who is credited for inventing the steam engine and enabling the Industrial Revolution.

to the signal applied, thereby allowing the signal to be visualized. Today, scanned beams are still used for ion implantation in the manufacture of integrated circuits.

Consider the simplified diagram of a CRT shown in Figure 1–1. If the electron beam carries 10^{14} electrons per second and is accelerated by a voltage of 50 kV, find the power in the beam.

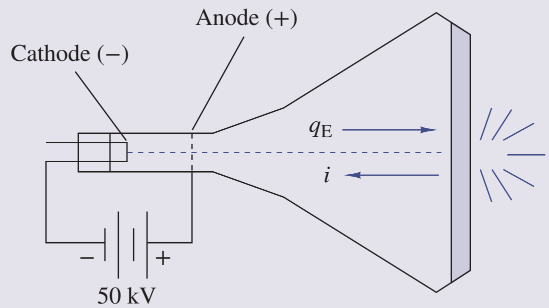

FIGURE 1–1

SOLUTION:
Since current is the rate of positive charge flow, its direction is opposite that of the electron beam, as shown in Figure 1–1. The electrons are flowing to the right from the cathode toward the anode, but the current i is flowing to the left toward the cathode. We can find the magnitude of the current by multiplying the magnitude of the charge of an electron q_E by the rate of electron flow dn_E/dt.

$$i = |q_E|\frac{dn_E}{dt} = (1.6\times10^{-19})(10^{14}) = 1.6\times10^{-5}\text{ A} = 16\,\mu\text{A}$$

Therefore, the beam power is

$$p = vi = (50\times10^{3})(1.6\times10^{-5}) = 0.8\text{ W} = 800\text{ mW}$$

■

EXAMPLE 1–2

The current through a circuit element is 50 mA. Find the total charge and the number of electrons transferred during a period of 100 ns.

SOLUTION:
The relationship between current and charge is given in Eq. (1–1) as

$$i = \frac{dq}{dt}$$

Since the current i is given, we calculate the charge transferred by solving this equation for dq and then integrating

$$\begin{aligned} q_T &= \int_{q_1}^{q_2} dq = \int_0^{10^{-7}} i\,dt \\ &= \int_0^{10^{-7}} 50\times10^{-3}\,dt = 50\times10^{-10}\text{ C} = 5\text{ nC} \end{aligned}$$

There are $1/|q_E| = 6.25\times10^{18}$ electrons/coulomb, so the number of electrons transferred is

$$n_E = (5\times10^{-9}\text{ C})(6.25\times10^{18}\text{ electrons/C}) = 31.25\times10^{9}\text{ electrons}$$

■

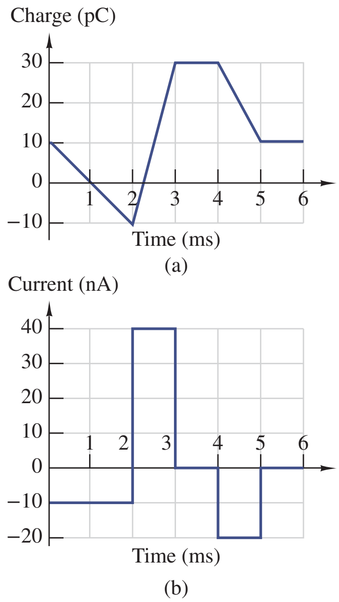

FIGURE 1–2

Exercise 1–2

A device dissipates 100 W of power. How much energy is delivered to it in 10 seconds?

Answer: 1 kJ

Note: 1 W-s = 1 J

Exercise 1–3

The graph in Figure 1–2(a) shows the charge $q(t)$ flowing past a point in a wire as a function of time.

(a) Find the current $i(t)$ at $t = 1$, 2.5, 3.5, 4.5, and 5.5 ms.
(b) Sketch the variation of $i(t)$ versus time.

Answers:

(a) −10 nA, +40 nA, 0 nA, −20 nA, 0 nA.
(b) The variations in $i(t)$ are shown in Figure 1–2(b).

The Passive Sign Convention

We have defined three circuit variables (current, voltage, and power) using two basic variables (charge and energy). Charge and energy, like mass, length, and time, are basic concepts of physics that provide the scientific foundation for electrical engineering. However, engineering problems rarely involve charge and energy directly, but are usually stated in terms of voltage, current, and power. The reason for this is simple: The circuit variables are much easier to measure and therefore are the most useful working variables in engineering practice.

At this point, it is important to stress the physical differences between current and voltage variables. Current is a measure of the time rate of charge passing a point in a circuit. We think of current as a *through variable*, since it describes the flow of electrical charge through a point in a circuit. On the other hand, voltage is not measured at a single point, but rather between two points or across an electrical device. Consequently, we think of voltage as an *across variable* that inherently involves two points.

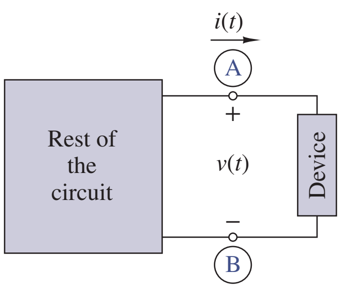

FIGURE 1–3 *Voltage and current reference marks for a two-terminal device.*

The arrow below the $i(t)$ and the plus and minus symbols across the $v(t)$ in Figure 1–3 are *reference marks* that define the positive directions for the current and voltage associated with an electrical device. These reference marks do not represent an assertion about what is happening physically in the circuit. The response of an electrical circuit is determined by physical laws, not by the reference marks assigned to the circuit variables.

The reference marks are benchmarks assigned at the beginning of the analysis. When the actual direction and reference direction agree, the answers found by circuit analysis will have positive algebraic signs. When they disagree, the algebraic signs of the answers will be negative. For example, if circuit analysis reveals that the current variable in Figure 1–3 is positive [i.e., $i(t) > 0$], then the sign of this answer, together with the assigned reference direction, indicates that the current passes through point A in Figure 1–3 from left to right. Conversely, when analysis reveals that the current variable is negative, then this result, combined with the assigned reference direction, tells us that the current passes through point A from right to left.