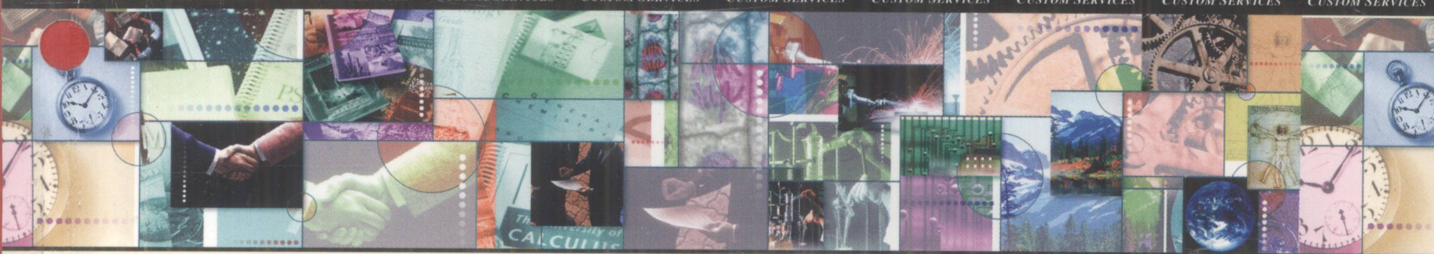


THE ANALYSIS & DESIGN OF

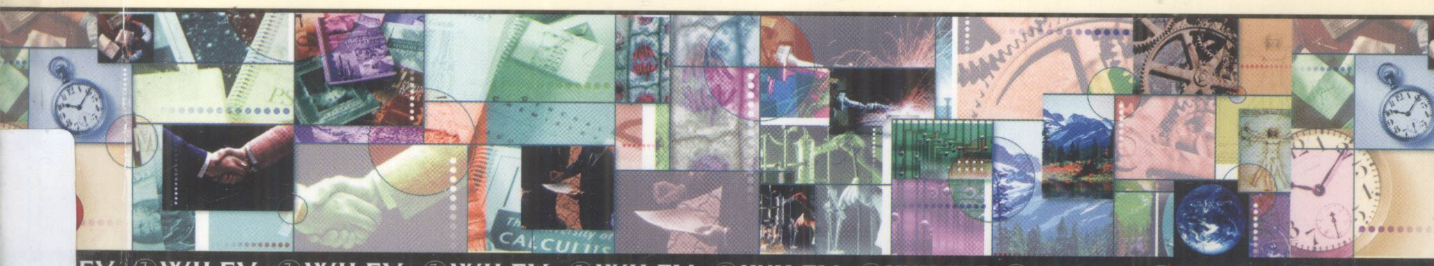
LINEAR CIRCUITS

sixth edition

SPECIAL EDITION

ROLAND E. THOMAS • ALBERT J. ROSA • GREGORY J. TOUSSAINT

WILEY Custom
LEARNING SOLUTIONS



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THE ANALYSIS AND DESIGN OF LINEAR CIRCUITS

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BASIC LAPLACE TRANSFORMATION PROPERTIES

PROPERTIES	TIME DOMAIN	FREQUENCY DOMAIN
Independent variable	t	s
Signal representation	$f(t)$	$F(s)$
Uniqueness	$\mathscr{L}^{-1}\{F(s)\}(=)[f(t)]u(t)$	$\mathscr{L}\{f(t)\} = F(s)$
Linearity	$Af_1(t) + Bf_2(t)$	$AF_1(s) + BF_2(s)$
Integration	$\int_0^t f(\tau)\,d\tau$	$\frac{F(s)}{s}$
Differentiation	$\frac{df(t)}{dt}$	$sF(s) - f(0-)$
	$\frac{d^2f(t)}{dt^2}$	$s^2F(s) - sf(0-) - f'(0-)$
	$\frac{d^3f(t)}{dt^3}$	$s^3F(s) - s^2f(0-) - sf'(0-) - f''(0-)$
s-Domain translation	$e^{-\alpha t}f(t)$	$F(s+\alpha)$
t-Domain translation	$f(t-a)u(t-a)$	$e^{-as}F(s)$

BASIC LAPLACE TRANSFORM PAIRS

SIGNAL	WAVEFORM $f(t)$	TRANSFORM $F(s)$
Impulse	$\delta(t)$	1
Step function	$u(t)$	$\frac{1}{s}$
Ramp	$tu(t)$	$\frac{1}{s^2}$
Exponential	$[e^{-\alpha t}]u(t)$	$\frac{1}{s+\alpha}$
Damped ramp	$[te^{-\alpha t}]u(t)$	$\frac{1}{(s+\alpha)^2}$
Sine	$[\sin \beta t]u(t)$	$\frac{\beta}{s^2+\beta^2}$
Cosine	$[\cos \beta t]u(t)$	$\frac{s}{s^2+\beta^2}$
Damped sine	$[e^{-\alpha t}\sin \beta t]u(t)$	$\frac{\beta}{(s+\alpha)^2+\beta^2}$
Damped cosine	$[e^{-\alpha t}\cos \beta t]u(t)$	$\frac{(s+\alpha)}{(s+\alpha)^2+\beta^2}$

STANDARD VALUES

THE RESISTOR COLOR CODE

Color	First Significant Digit	Second Significant Digit	Multiplier	Tolerance
None				±20%
Silver			0.01	±10%
Gold			0.1	±5%
Black	0	0	1	
Brown	1	1	10	±1%
Red	2	2	100	±2%
Orange	3	3	1k	
Yellow	4	4	10k	
Green	5	5	100k	
Blue	6	6	1000k	
Violet	7	7		
Gray	8	8		
White	9	9		

STANDARD VALUES FOR RESISTORS

Value	Tolerances	Value	Tolerances	Value	Tolerances
10	±5%, ± 10%, ± 20%	22	±5%, ± 10%, ± 20%	47	±5%, ± 10%, ±
11	±5%	24	±5%	51	±5%
12	±5%, ± 10%	27	±5%, ± 10%	56	±5%, ± 10%
13	±5%	30	±5%	62	±5%
15	±5%, ± 10%, ± 20%	33	±5%, ± 10%, ± 20%	68	±5%, ± 10%, ±
16	±5%	36	±5%	75	±5%
18	±5%, ± 10%	39	±5%, ± 10%	82	±5%, ± 10%
20	±5%	43	±5%	91	±5%

STANDARD VALUES FOR CAPACITORS

pF	pF	pF	pF	μF	μF	μF	μF	μF	μF	μF
1.0	10	100	1000	0.01	0.1	1.0	10	100	1000	10.000
1.1	11	110	1100							
1.2	12	120	1200							
1.3	13	130	1300							
1.5	15	150	1500	0.015	0.15	1.5	15	150	1500	
1.6	16	160	1600							
1.8	18	180	1800							
2.0	20	200	2000							
2.2	22	220	2200	0.022	0.22	2.2	22	220	2200	
2.4	24	240	2400							
2.7	27	270	2700							
3.0	30	300	3000							
3.3	33	330	3300	0.033	0.33	3.3	33	330	3300	
3.6	36	360	3600							
3.9	39	390	3900							
4.3	43	430	4300							
4.7	47	470	4700	0.047	0.47	4.7	47	470	4700	
5.1	51	510	5100							
5.6	56	560	5600							
6.2	62	620	6200							
6.8	68	680	6800	0.068	0.68	6.8	68	680	6800	
7.5	75	750	7500							
8.2	82	820	8200							
9.1	91	910	9100							

STANDARD VALUES FOR INDUCTORS

nH, μH			
1.0	10	100	1000
1.1	11	110	1100
1.2	12	120	1200
1.3	13	130	1300
1.5	15	150	1500
1.6	16	160	1600
1.8	18	180	1800
2.0	20	200	2000
2.2	22	220	2200
2.4	24	240	2400
2.7	27	270	2700
3.0	30	300	3000
3.3	33	330	3300
3.6	36	360	3600
3.9	39	390	3900
4.3	43	430	4300
4.7	47	470	4700
5.1	51	510	5100
5.6	56	560	5600
6.2	62	620	6200
6.8	68	680	6800
7.5	75	750	7500
8.2	82	820	8200
8.7	87	870	8700
9.1	91	910	9100

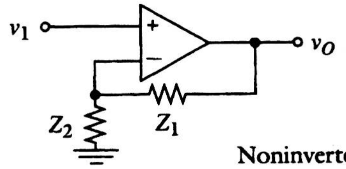
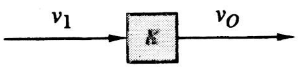
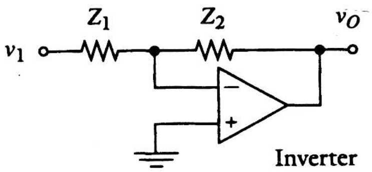
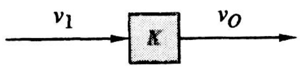
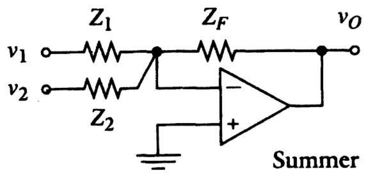
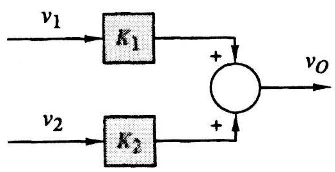
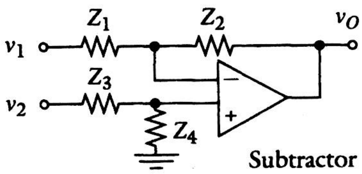
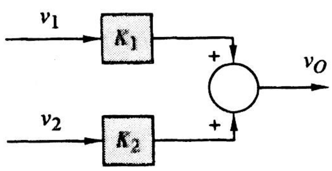
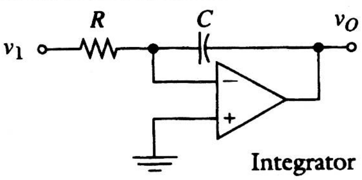
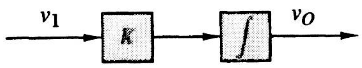
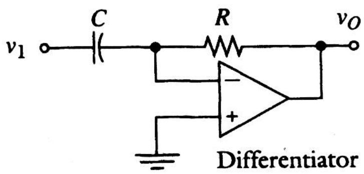
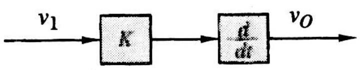
ELECTRICAL QUANTITIES

Quantity	Symbol	Unit	Unit Abbreviation
Time	t	second	s
Frequency	f	hertz	Hz
Radian frequency	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	$\mathcal{E}$	volt/meter	V/m
Voltage	v	volt	V
Impedance	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

BASIC OP AMP MODULES

Circuit	Block Diagram	Gains
 Noninverter		$K = \dfrac{Z_1 + Z_2}{Z_2}$
 Inverter		$K = -\dfrac{Z_2}{Z_1}$
 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		$K = -RC$

THE ANALYSIS AND DESIGN OF LINEAR CIRCUITS

To our wives
Juanita, Kathleen, and Tricia

PREFACE

Why This Text?

Our approach to circuits in this text differs from others. It recognizes that studying circuits can be rewarding and useful, even for students who are not majoring in electrical or computer engineering. Most students who pursue engineering studies are looking for opportunities to be creative and design things. The longer it takes them to encounter such opportunities, the more likely it is that they will become disillusioned and perhaps change to a different major. The authors 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 teaching experience at several institutions have 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 are more likely to solve problems using computers than by hand or even with a calculator. Access to personal computers 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 many more software examples, exercises, and discussions geared to making the study of circuits more in line with today's student. Our text has always included software, but generally as an extension for solving circuits by hand. This edition, however, integrates software intimately into the solution of circuit problems whenever and wherever it really helps to solve the problems. It still recognizes that using computers does not replace the intuition that engineers must develop to analyze, design, and make smart judgments about different working solutions or designs. To help us integrate this approach smoothly into our text, we included Dr. Gregory Toussaint, a software and signals and systems expert, into our partnership. He has extensive experience teaching, using earlier editions of our text, and educating with MATLAB®.

The sixth edition of *The Analysis and Design of Linear Circuits* improves on the fifth edition and remains friendly to users of both versions of the fourth edition, those who prefer a *Laplace Early* approach or those favoring the more traditional *Phasor First* approach to ac circuits. A later section discusses how to use this text to pursue either a traditional Phasor First approach or the Laplace Early approach. The sixth edition assumes the same student prerequisites as past editions but does rely more on students having access to personal computers. This edition targets students of all engineering disciplines who need an introductory circuit analysis course of one or two terms. The sixth edition continues the authors' combined commitment of over 50 years to providing a modern and innovative approach to teaching circuit analysis and design.

Continuing Features

Objectives

This text remains structured around a sequence of carefully defined 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 or CLOs. 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 six 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, there must be an assessment and evaluation process that periodically documents and demonstrates the degree to which the program outcomes are attained.)

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)—specifically, the ability to design a system. We identify design Examples, exercises, and homework problems with a **D** icon.

Design evaluation

Realistic design problems do not have unique solutions, so it is natural for students to wonder how their designs compare with those of others. An often-asked question is "Is my design a good one?" Using judgment to compare alternative solutions is a fundamental trait of good engineering. The evaluation of alternative designs introduces students to real-world engineering practice. Including design and the evaluation of design in an introductory course helps to convince students that circuits perform useful functions and that circuit design courses are not simply vehicles for teaching routine skills such as node-voltage and mesh-current analyses. Although this philosophy is implicit in all previous editions, this edition offers expanded coverage of design and evaluation both in the worked examples and in the homework problems. We use software extensively to help students visualize specifications and 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 meet desired needs 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 a **D** icon.

THE OP AMP

An early introduction and integrated treatment of the OP AMP is again a central feature of this text. The modular form of OP AMP circuits simplifies analog circuit analysis and design by minimizing the effects of loading and allowing the interconnection of simple building blocks to produce complex signal processing functions. 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, which have been expanded in this new edition, are especially useful to students from other engineering disciplines that require knowledge of instrumentation, filtering, or signal processing.

LAPLACE TRANSFORMS

In electrical engineering, 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 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. The authors 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.

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 new concepts. A further emphasis on signal processing and systems is achieved through the use of block diagrams, input-output relationships, and transforms 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. Viewing signals in both domains naturally leads to discussions of important concepts like 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 students come to the circuits course already knowing how to use several useful computer tools. Although many know how to use Excel and may be familiar with MATLAB and/or OrCAD, our goal 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. Three types of computer programs are used to illustrate computer-aided circuit analysis, namely spreadsheets (Excel®), math solvers (MATLAB®), and circuit simulators (OrCAD®). Examples, exercises, and homework problems related to computer-aided circuit analysis are integrated into all chapters, beginning with Chapter 1. The purpose of the examples is to help students develop a problem-solving style that includes the intelligent use of the productivity tools routinely used by practicing engineers. Exercises following the examples help students immediately practice the software skill demonstrated in the example. Homework problems that require the use of a particular computer tool are identified by a computer icon (). This approach 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 relate 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 and find use in common applications and products. These examples can be used to support ABET Criterion 3(j)—a knowledge of contemporary issues.

WEB CHAPTER AND APPENDICES

The sixth edition continues the chapter-length treatment of *two-port networks* as a Web chapter. This chapter is fully integrated into the text, with index references and answers to selected homework problems. This chapter is available at *www.wiley.com/college/thomas.* Also available on the web are two appendices one on the solution of linear equations and one on Butterworth and Chebychev Poles.

NEW FEATURES FOR THE SIXTH EDITION

EXTENSIVE USE OF SOFTWARE

Software use throughout the text has been increased and strengthened to include 41 new MATLAB examples and 20 new OrCAD examples. We have added

24 new MATLAB exercises and 15 new OrCAD exercises to help practice using the software. We have added four new or revised sections (1–4, 2–7, 5–7, and 9–5) and a new Appendix B to simplify students' use of software. There are 228 new homework problems that require solution using MATLAB, OrCAD, or both.

CIRCUIT DESIGN AND EVALUATION

Forty-five design and 15 evaluation examples are new to this edition. Our emphasis on creating solutions and choosing the better or best one has been strengthened with the inclusion of 141 new design and 41 new evaluation homework problems. Here is a sample listing of evaluation examples:

Page	*Example*	*Topic*
125	3–22	Interface circuit design
184	4–17	Block diagram realization
197	4–20	Transducer interface design
328	7–11	First-order *RC* circuits
553	11–7	Cascade connection loading mitigation
586	11–23	Active step-response circuit design
622	12–9	Bandstop filter design
657	12–22	Piezoelectric pressure transducers
766	14–8	Multipole low-pass filter
824	16–7	Power distribution circuit

OP AMPS

The treatment of OP AMPs in Chapter 4 has been revised to further emphasize *design* and *evaluation*. The section "OP AMP Applications" has been expanded to include more practical examples for interfacing transducers. Added are interfacing passive transducers, such as strain gauges, for example.

FREQUENCY RESPONSE AND ACTIVE FILTERS

We have revised Chapter 12 on frequency response, and Chapter 14, on active filters. These chapters are excellent means of mastering software tools, and we have noted this in our rewrites. Bode diagrams, for example, had been primarily a hand-drawing exercise with just a mention of software use. In our rewrite, we recognize that MATLAB can generate Bode diagrams easily and that designed circuits can have their frequency responses plotted effortlessly using OrCAD. 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 expanded our coverage of active multipole high-pass filters to match that of low-pass filters. We also expanded our coverage of consideration of a filter's transient behavior in choosing the best filter solution. Both chapters have more design and evaluation examples as well as more homework problems.

FOURIER ANALYSIS

We have restored the Fourier transform discussion in Chapter 13 from the Web chapter used in the last few editions and retitled it "Fourier Analysis." This chapter contains descriptions of both Fourier series and Fourier transforms. In addition to demonstrating Fourier analysis with signals, the chapter emphasizes how to apply Fourier techniques to simplify circuit analysis.

AC POWER SYSTEMS

We have extensively revised Chapter 16, on ac power, to make it more in line with what today's students should know. The focus is away from phasor circuit analysis toward power flow and systems, both single-phase and three-phase.

USING THIS EDITION FOR *LAPLACE EARLY*

The sixth 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 to 11). Those wishing to follow the traditional approach can follow the sixth 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 uses 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 appendix to allow the construction of other topic sequences. Other organizational options are available in the Instructor Manual.

	Semester 1							Semester 2							
Traditional	**1**	**2**	**3**	**4**	**5**	**6**	**8/7**								
Power								7/8	15	16	9	10	11	12	13
Systems								7/8	9	10	11	12	13	14	15
Electronics								7/8	9	10	11	12	14	15	Web
Laplace Early	**1**	**2**	**3**	**4**	**5**	**6**	**7**								
Power								9	10	11	12	13	8	15	16
Systems								9	10	11	12	13	14	8	15
Electronics								9	10	11	12	14	8	15	Web

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