

This International Student Edition is for use outside of the U.S.

Engineering Circuit Analysis

Ninth Edition



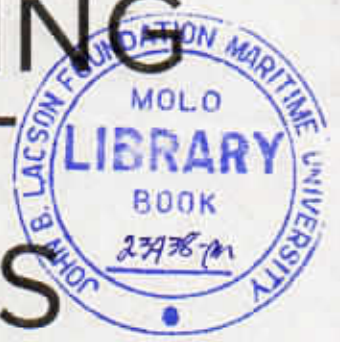
**Mc
Graw
Hill**
Education

William H. Hayt, Jr. • Jack E. Kemmerly
Jamie D. Phillips • Steven M. Durbin

60
4213192
H926
7019

CPE 7998-

ENGINEERING CIRCUIT ANALYSIS



PREFACE XV

CHAPTER 1

INTRODUCTION 1

- 1.1 Overview of Text 2
 - 1.2 Relationship of Circuit Analysis to Engineering 5
 - 1.3 Analysis and Design 6
 - 1.4 Computer-Aided Analysis 7
 - 1.5 Successful Problem-Solving Strategies 9
- READING FURTHER 10

CHAPTER 2

BASIC COMPONENTS AND ELECTRIC CIRCUITS 11

- 2.1 Units and Scales 11
 - 2.2 Charge, Current, Voltage, Power, and Energy 13
 - 2.3 Voltage and Current Sources 21
 - 2.4 Ohm's Law 25
- SUMMARY AND REVIEW 33
READING FURTHER 34
EXERCISES 34

CHAPTER 3

VOLTAGE AND CURRENT LAWS 43

- 3.1 Nodes, Paths, Loops, and Branches 43
 - 3.2 Kirchhoff's Current Law 44
 - 3.3 Kirchhoff's Voltage Law 46
 - 3.4 The Single-Loop Circuit 50
 - 3.5 The Single-Node-Pair Circuit 53
 - 3.6 Series and Parallel Connected Sources 55
 - 3.7 Resistors in Series and Parallel 59
 - 3.8 Voltage and Current Division 65
- SUMMARY AND REVIEW 70
READING FURTHER 71
EXERCISES 71

CHAPTER 4

BASIC NODAL AND MESH ANALYSIS 85

- 4.1 Nodal Analysis 86

- 4.2 The Supernode 95
 - 4.3 Mesh Analysis 99
 - 4.4 The Supermesh 106
 - 4.5 Nodal vs. Mesh Analysis: A Comparison 109
 - 4.6 Computer-Aided Circuit Analysis 111
- SUMMARY AND REVIEW 114
READING FURTHER 117
EXERCISES 117

CHAPTER 5

HANDY CIRCUIT ANALYSIS TECHNIQUES 133

- 5.1 Linearity and Superposition 133
 - 5.2 Source Transformations 144
 - 5.3 Thévenin and Norton Equivalent Circuits 152
 - 5.4 Maximum Power Transfer 163
 - 5.5 Delta-Wye Conversion 166
 - 5.6 Selecting an Approach: A Summary of Various Techniques 168
- SUMMARY AND REVIEW 169
READING FURTHER 170
EXERCISES 171

CHAPTER 6

THE OPERATIONAL AMPLIFIER 185

- 6.1 Background 185
 - 6.2 The Ideal Op Amp 186
 - 6.3 Cascaded Stages 195
 - 6.4 Feedback, Comparators, and the Instrumentation Amplifier 199
 - 6.5 Practical Considerations 209
- SUMMARY AND REVIEW 218
READING FURTHER 219
EXERCISES 219

CHAPTER 7

CAPACITORS AND INDUCTORS 229

- 7.1 The Capacitor 229

- 7.2 The Inductor 237
- 7.3 Inductance and Capacitance Combinations 247
- 7.4 Linearity and its Consequences 250
- 7.5 Simple Op Amp Circuits with Capacitors 252
- 7.6 Duality 254
- 7.7 Computer Modeling of Circuits with Capacitors and Inductors 257
- SUMMARY AND REVIEW 260
- READING FURTHER 261
- EXERCISES 261

CHAPTER 8

BASIC RC AND RL CIRCUITS 273

- 8.1 The Source-Free RC Circuit 273
- 8.2 Properties of the Exponential Response 277
- 8.3 The Source-Free RL Circuit 281
- 8.4 A More General Perspective 285
- 8.5 The Unit-Step Function 290
- 8.6 Driven RC Circuits 294
- 8.7 Driven RL Circuits 300
- 8.8 Predicting the Response of Sequentially Switched Circuits 303
- SUMMARY AND REVIEW 311
- READING FURTHER 313
- EXERCISES 313

CHAPTER 9

THE RLC CIRCUIT 325

- 9.1 The Source-Free Parallel Circuit 325
- 9.2 The Overdamped Parallel RLC Circuit 331
- 9.3 Critical Damping 339
- 9.4 The Underdamped Parallel RLC Circuit 343
- 9.5 The Source-Free Series RLC Circuit 351
- 9.6 The Complete Response of the RLC Circuit 357
- 9.7 The Lossless LC Circuit 365
- SUMMARY AND REVIEW 369
- READING FURTHER 370
- EXERCISES 370

CHAPTER 10

SINUSOIDAL STEADY-STATE ANALYSIS 381

- 10.1 Characteristics of Sinusoids 381
- 10.2 Forced Response to Sinusoidal Functions 384
- 10.3 The Complex Forcing Function 388

- 10.4 The Phasor 393
- 10.5 Impedance and Admittance 399
- 10.6 Nodal and Mesh Analysis 404
- 10.7 Superposition, Source Transformations, and Thévenin's Theorem 407
- 10.8 Phasor Diagrams 416
- SUMMARY AND REVIEW 419
- READING FURTHER 420
- EXERCISES 420

CHAPTER 11

AC CIRCUIT POWER ANALYSIS 431

- 11.1 Instantaneous Power 432
- 11.2 Average Power 434
- 11.3 Maximum Power Transfer 441
- 11.4 Effective Values of Current and Voltage 446
- 11.5 Apparent Power and Power Factor 451
- 11.6 Complex Power 454
- SUMMARY AND REVIEW 460
- READING FURTHER 461
- EXERCISES 462

CHAPTER 12

POLYPHASE CIRCUITS 471

- 12.1 Polyphase Systems 472
- 12.2 Single-Phase Three-Wire Systems 474
- 12.3 Three-Phase Y-Y Connection 478
- 12.4 The Delta (Δ) Connection 484
- 12.5 Power Measurement in Three-Phase Systems 490
- SUMMARY AND REVIEW 498
- READING FURTHER 500
- EXERCISES 500

CHAPTER 13

MAGNETICALLY COUPLED CIRCUITS 507

- 13.1 Mutual Inductance 507
- 13.2 Energy Considerations 515
- 13.3 The Linear Transformer 519
- 13.4 The Ideal Transformer 526
- SUMMARY AND REVIEW 535
- READING FURTHER 536
- EXERCISES 536

CHAPTER 14**CIRCUIT ANALYSIS IN THE s -DOMAIN 545**

- 14.1 Complex Frequency 545
- 14.2 Definition of the Laplace Transform 549
- 14.3 Laplace Transforms of Simple Time Functions 552
- 14.4 Inverse Transform Techniques 554
- 14.5 Basic Theorems for the Laplace Transform 561
- 14.6 The Initial-Value and Final-Value Theorems 568
- 14.7 $Z(s)$ and $Y(s)$ 571
- 14.8 Nodal and Mesh Analysis in the s -Domain 576
- 14.9 Additional Circuit Analysis Techniques 584
- 14.10 Poles, Zeros, and Transfer Functions 587
- 14.11 Convolution 589
- 14.12 A Technique for Synthesizing the Voltage Ratio
 $H(s) = V_{out}/V_{in}$ 599
- SUMMARY AND REVIEW 603
- READING FURTHER 605
- EXERCISES 606

CHAPTER 15**FREQUENCY RESPONSE 615**

- 15.1 Transfer Function 615
- 15.2 Bode Diagrams 618
- 15.3 Parallel Resonance 633
- 15.4 Bandwidth and High- Q Circuits 640
- 15.5 Series Resonance 646
- 15.6 Other Resonant Forms 649
- 15.7 Scaling 657
- 15.8 Basic Filter Design 660
- 15.9 Advanced Filter Design 669
- SUMMARY AND REVIEW 674
- READING FURTHER 676
- EXERCISES 676

CHAPTER 16**TWO-PORT NETWORKS 687**

- 16.1 One-Port Networks 687
- 16.2 Admittance Parameters 692
- 16.3 Some Equivalent Networks 699
- 16.4 Impedance Parameters 708
- 16.5 Hybrid Parameters 713
- 16.6 Transmission Parameters 716
- SUMMARY AND REVIEW 720
- READING FURTHER 721
- EXERCISES 722

CHAPTER 17**FOURIER CIRCUIT ANALYSIS 733**

- 17.1 Trigonometric Form of the Fourier Series 733
- 17.2 The Use of Symmetry 743
- 17.3 Complete Response to Periodic Forcing Functions 748
- 17.4 Complex Form of the Fourier Series 750
- 17.5 Definition of the Fourier Transform 757
- 17.6 Some Properties of the Fourier Transform 761
- 17.7 Fourier Transform Pairs for Some
Simple Time Functions 764
- 17.8 The Fourier Transform of a General Periodic
Time Function 769
- 17.9 The System Function and Response
in the Frequency Domain 770
- 17.10 The Physical Significance of the System Function 777
- SUMMARY AND REVIEW 782
- READING FURTHER 783
- EXERCISES 783

**APPENDIX 1 AN INTRODUCTION TO NETWORK
TOPOLOGY 791****APPENDIX 2 SOLUTION OF SIMULTANEOUS
EQUATIONS 803****APPENDIX 3 A PROOF OF THÉVENIN'S
THEOREM 811****APPENDIX 4 AN LTspice® TUTORIAL 813****APPENDIX 5 COMPLEX NUMBERS 817****APPENDIX 6 A BRIEF MATLAB® TUTORIAL 827****APPENDIX 7 ADDITIONAL LAPLACE TRANSFORM
THEOREMS 833****APPENDIX 8 THE COMPLEX FREQUENCY PLANE 839**

INDEX 847

ADDITIONAL CONTENT 861

A

- abc phase sequence, 478
- Abscissa, 657
- Absorbed power, 18
- AC circuit power analysis, 431–470
 - apparent power and power factor, 451–455, 466
 - average power, 434–441, 455, 462–464
 - absorbed by an ideal resistor, 437–438
 - absorbed by purely reactive elements, 438
 - for nonperiodic functions, 440–441
 - not to be confused with instantaneous power, 438
 - for periodic waveforms, 435
 - in the sinusoidal steady state, 435–436
 - complex power, 454–459, 467–468
 - power measurement, 456
 - power triangle, 456
 - reactive power, 454–455
 - computer-aided analysis, 449–451
 - effective values of current and voltage, 446–451, 464–465
 - effective value of periodic waveform, 446–447
 - effective (RMS) value of sinusoidal waveform, 447–448
 - effective value with multiple-frequency circuits, 448–449
 - use of RMS values to compute average power, 448
- instantaneous power, 432–434, 462
 - power due to sinusoidal excitation, 433
- LTspice, 449–451
- maximum power transfer, 441–446, 464
 - average power delivered to load, 442–443
 - impedance matching, 443–446
 - practical application: power factor correction, 457–458
 - summary and review, 460–461
- AC power terms, summary of, 460
 - apparent power, 460
 - average power, 460
 - complex power, 460
 - effective or rms value, 460
 - instantaneous power, 460
 - power factor, 460
 - reactive power, 460
- Active filters, 666–667
- Admittance and impedance, 399–404, 424–425
 - admittance, 404
 - parameters, two-port networks, 692–699, 723–725
 - parallel impedance combinations, 399–400
 - reactance, 400–404
 - series impedance combinations, 399
- Advanced filter design
 - frequency response, 669–674, 685
 - Butterworth filters, 670–674
 - Chebyshev filters, 670–672, 674
 - Sallen-Key amplifier, 671–674
- Algebraic alternative to differential equations, 390–391
- Ampère, A.M., 14, 237
- Amperes, 12–14
- Analysis, defined, 6
- Analysis and design, 6
- Analytical Engine, 6, 8
- Apparent power, 451–452, 460
 - power factor and, 451–455, 466
- Argand diagram, 817
- Asymptotes, determination of
 - Bode diagrams, 619–620
- Attenuators, 188, 599
- Automated defibrillators, 364
- Auxiliary equation, 328
- Average power, 434–441, 455, 460, 462–464
 - absorbed by an ideal resistor, 437–438

- absorbed by purely reactive elements, 438
- delivered to load, 442–443
- for nonperiodic functions, 440–441
- not to be confused with instantaneous power, 438
- for periodic waveforms, 435
- in the sinusoidal steady state, 435–436

B

- Babbage, Charles, 8
- Bandpass filters, 661, 663–666
- Bandstop filters, 661
- Bandwidth and high- Q circuits
 - frequency response, 640–646, 680–681
 - approximations for high- Q circuits, 642–646
 - bandwidth, 641–642
- Basic components and electric circuits, 11–42
 - charge, 13–14, 35–39
 - computer-aided analysis, 30–31
 - current, 35–39
 - damped sinusoidal current, 15
 - direct current (dc), 15
 - exponential current, 15
 - sinusoidal current (ac), 15
 - energy, 19–21, 35–39
 - Ohm's law, 25–33, 39–41
 - conductance, 30–31
 - fuses, 30
 - power absorption, 26–27
 - practical application (wire gauge), 28–29
 - power (p), 17–19, 35–39
 - absorbed, 18
 - negative, 18
 - passive sign convention, 18
 - supplied, 18
 - summary and review, 33–34
 - units and scales, 11–13, 34–35
 - voltage, 16, 35–39
 - defined, 16

- Basic components . . . (Continued)
 voltage and current sources, 20–25, 39
 dependent sources, 22–23
 independent current sources, 22
 independent voltage sources, 21–22
 networks and circuits, 24–25
- Basic filter design
 frequency response, 660–669, 683–685
 active filters, 666–667
 bandpass filters, 663–666
 passive low-pass and high-pass filters, 661–663
- Bass, treble, and midrange adjustment, 668–669
- Battery capacity, 20
- Bode, Hendrik W., 618
- Bode diagrams, 618–632, 678–679
 complex conjugate pairs, 627–629
 computer-aided analysis, 630–632
 decibel (dB) scale, 618–619
 determination of asymptotes, 619–620
 higher-order terms, 626–627
 multiple terms, 620–621
 phase response, 621–622
 smoothing Bode plots, 620
 using MATLAB, 630–632
- Branch
 defined, 791
 voltage and current laws, 44, 71–72
- Break frequency, 619
- Buffers, 190
- Butterworth filters, 670–674
- Butterworth polynomial, 670
- C**
- C (Coulomb), 13
- CAD (computer-aided design)
 for rapid analysis of circuits, 111
- Candela, 12
- Capacitors and inductors, 229–272
 capacitors, 229–237, 261–264
 energy storage, 234–237
 ideal capacitor model, 229–232, 237
- integral voltage–current relationships, 232–234
- computer modeling of circuits with capacitors and inductors, 257–259, 271–272
- duality, 245, 254–257, 270–271
- inductance and capacitance combinations, 247–250, 266–268
- capacitors in parallel, 249–250
 capacitors in series, 248–249
 inductors in parallel, 248
 inductors in series, 247–248
- inductors, 237–246, 264–266
 energy storage, 243–245
 ideal inductor model, 237–241, 245
- integral voltage–current relationships, 241–243
- linearity and its consequences, 250–252, 268–269
- practical application: in search of the missing element (the memristor), 246
- simple op amp circuits with capacitors, 252–253, 269–270
- summary and review, 260–261
- Cascaded stages
 operational amplifiers (OAs), 195–199, 221–223
- Cavendish, Henry, 26
- cba phase sequence, 478
- Characteristic equation, 328
- Characterizing transistors, 715–716
- Charge, 13–14, 35–39
- Chassis ground, 69
- Chebyshev filters, 670–672, 674
- Chebyshev polynomial, 670
- Chua, Leon, 236
- Circuit
 defined, 24
 elements of, 21, 24
- Circuit analysis, relationship to engineering, 5–6
 “translating” relevant variables, 5
- Circuit analysis techniques, 133–184
 delta–wye conversion, 166–168, 181–183
 linearity and superposition, 133–144, 171–173
 computer-aided analysis, 141–143
- limitations of superposition, 143–144
- linear circuit, defined, 134
- linear dependent source, defined, 134
- linear element, defined, 133
- linear elements and linear circuits, 133–134
- linear voltage–current relationship, defined, 133–134
- superposition, defined, 133
- superposition principle, 134–136
- superposition procedure, summarized, 140
- LTspice
 circuits in the sinusoidal steady state, analyzing, 414–415
 circuits that contain magnetically coupled inductances, simulating, 524–526
 circuits with capacitors and inductors, modeling, 257–259
- maximum power transfer, 163–165, 179–181
- theorem, 163
- practical application: digital multimeter (DMM), 161–162
- s*-domain. *See s*-domain circuit analysis
- selecting an approach, 168–169, 183
- source transformations, 144–151, 173–176
 equivalent practical sources, 146–147
 key points, 150–151
 practical current sources, 146
 practical voltage sources, 144–145
 procedure, summarized, 151
- summary and review, 169–170
- Thévenin and Norton equivalent circuits, 4, 152–162, 176–179
 key points, 155–156
 Norton’s theorem, 4, 156
 procedure recap, 160, 162
 Thévenin equivalent resistance, 155
 Thévenin’s theorem, 4, 154
 when dependent sources are present, 158

- CMRR (common-mode rejection ratio), 212
- Coefficient of mutual inductance, 508
- Column matrix, 804
- Common-mode rejection, 212
 common-mode rejection ratio (CMRR), 212
 operational amplifiers (OAs), 212
- Comparators, 201–206
 computer-aided analysis, 201–202
 feedback, 201–206
 hysteresis, 204
 memory, 204
 positive feedback configuration, 203–204
 Schmitt trigger, 204–206
- Complete response to periodic forcing functions
 Fourier circuit analysis, 748–750, 786
- Complex conjugate, 547
- Complex conjugate pairs
 Bode diagrams, 627–629
- Complex forcing function, 388–392, 422–423
 algebraic alternative to differential equations, 390–391
 applying, 389–390
 imaginary sources lead to imaginary responses, 389
- Complex form of Fourier series, 750–757, 787
 sampling function, 754–757
- Complex frequency, 330
 s -domain circuit analysis, 545–549, 606
 DC case, 547
 exponential case, 547
 exponentially damped sinusoidal case, 548
 general form, 546–547
 neper frequency, 546
 relationship of s to reality, 548–549
 sinusoidal case, 547
- Complex frequency plane, 839–846
 general perspective, 843–844
 special case, 844
- Complex numbers, 817–826
 defined, 817
 Euler's identity, 820–821
 exponential form, 822–824
 introduction, 817–820
 polar form, 824–826
- Complex plane, 817
- Complex power, 454–460, 467–468
 power measurement, 456
 power triangle, 456
 reactive power, 454–455
- Components and electric circuits. *See*
 Basic components and electric circuits
- Computer-aided analysis, 6–9
- Computer-aided design (CAD)
 for rapid analysis of circuits, 111
- Conductance, 404
 Ohm's law, 30–31
- Conjugates, 547
 of complex numbers, 819
- Constant forcing function, 766
- Convolution
 s -domain circuit analysis, 589–598, 613–614
 convolution and realizable systems, 591–592
 convolution integral, 591
 graphical method of convolution, 592–593
 impulse response, 590–591
 Laplace transform and, 595–596
 transfer functions, further comments on, 597
- Corner frequency, 619
- Cosines, 383–384
- Cotrees, 792–793
- Coulomb (C), 13
- Coupling coefficient, 518
- Cramer's rule, 688, 809–810
- Critical damping, RLC circuit, 339–343, 347, 353, 372–373
 finding values for A_1 and A_2 , 340–341
 form of a critically damped response, 340
 graphical representation of critically damped response, 341–343
- Current, 35–39
 damped sinusoidal current, 15
 defined, 13–14
 direct current (dc), 15
 exponential current, 15
 sinusoidal current (AC), 15
- Current adjustment, use of transformers for, 528–529
- Current and voltage, effective values of, 446–451, 464–465
 effective value of periodic waveform, 446–447
 effective (RMS) value of sinusoidal waveform, 447–448
 effective value with multiple-frequency circuits, 448–449
 use of RMS values to compute average power, 448
- Current and voltage laws, 43–84
 branches, 44, 71–72
 Kirchhoff's current law (KCL), 43–46, 72–74
 Kirchhoff's voltage law (KVL), 43, 46–50, 74–76
 loops, 44, 71–72
 nodes, 44, 71–72
 distributed-parameter network, 43
 lumped-parameter network, 43
 paths, 44, 71–72
 practical application: ground connections, 69–70
 chassis ground, 69
 earth ground, 69
 signal ground, 69
 resistors in series and parallel, 59–65, 79–81
 series and parallel connected sources, 55–59, 78–79
 single-loop circuits, 50–53, 76–77
 single-node-pair circuits, 53–55, 77–78
 summary and review, 70–71
 voltage and current division, 65–68, 81–82
- Current and voltage sources, 20–25, 39
 dependent sources, 22–23
 independent current sources, 22
 independent voltage sources, 21–22
 networks and circuits, 24–25
 cutoff frequency of transistor amplifier, 408–409

D

- Damped sinusoidal current, 15
- Damping factor, 627, 639–640
- Damping oscillations, 326–327
- dc (direct current), 15
 - analysis, 4
 - current source, 22
 - parameter sweep
 - LTspice, 141–143
 - voltage source, 22
- Decade, 619
- Decibel (dB), 618–619
- Deep Learning Neural Network processor, 7
- Delta (Δ) connection
 - polyphase circuits, 484–487, 503–504
 - Δ -connected sources, 487, 490
- Delta-*wye* conversion, 166–168, 181–183
- Dependent sources, 22–23, 288
- Designed
 - defined, 6
- Determinants (matrix), 807–809
- Determination of asymptotes
 - Bode diagrams, 619–620
- Difference amplifiers, 191–192
- Differential equation
 - obtaining for a parallel *RLC* circuit, 327–328
 - solution for a parallel *RLC* circuit, 328–329
- Differential input voltage, 211
- Digital multimeter (DMM), 161–162
- Digital power meter, clamp-on, 456
- Direct current (dc). *See* dc (direct current)
- Discrete spectrum, 742
- Distributed-parameter network, 43
- DMM (digital multimeter), 161–162
- Dot convention, 509–515
- Double-subscript notation, 473–474
- Driven *RC* circuits, 294–300, 319–321
 - complete response, determination of, 295–297
 - developing an intuitive understanding, 300
 - forced response, 295
 - natural response, 294–295

- Driven *RL* circuits, 300–302, 321–322
- Duality
 - capacitors and inductors, 245, 254–257, 270–271

E

- Earth ground, 69
- ECG (electrocardiogram), 208–209
- Edison, Thomas, 471
- Effective or RMS value, 460
- Effective values of current and voltage, 446–451, 464–465
 - effective value of periodic waveform, 446–447
 - effective (RMS) value of sinusoidal waveform, 447–448
 - effective value with
 - multiple-frequency circuits, 448–449
 - use of RMS values to compute average power, 448
- Electrical wire materials and resistivities, 28
- Electric circuits and basic components. *See* Basic components and electric circuits
- Electrocardiogram (ECG), 208–209
- Energy, 19–21, 35–39
- Energy density, 763
- Energy storage
 - capacitors, 234–237
 - inductors, 243–245
- ENIAC, 8
- Equivalent circuits
 - ideal transformers, 532–535
- Equivalent networks
 - two-port networks, 699–707, 725–727
- Equivalent practical sources, 146–147
- Euler's identity
 - complex numbers, 820–821
- Even and odd symmetry, 743
 - Fourier circuit analysis, 743
- Exponential current, 15
- Exponential damping coefficient frequencies, 329
- Exponential form of complex numbers, 822–824

- Exponential response, properties of, 277–281, 314–315
 - RC* and *RL* circuits, basic, 277–281, 314–315
 - time constant, 278–280

F

- F (farad), 230
- Faraday, Michael, 237
- Feedback, 199–201
 - negative, 199–201
 - operational amplifiers (OAs), 199–209, 223–226
 - positive, 199–201, 203
- Fiber optic intercom, 193–194
- Filter design, frequency response, 660–669, 683–685
 - active filters, 666–667
 - bandpass filters, 663–666
 - passive low-pass and high-pass filters, 661–663
- Finite resistance, 346–347
- Finite wire impedance, 475
- Forced response, 384, 733–734
 - driven *RC* circuits, 295
 - source-free *RC* circuits, 274
- Fourier circuit analysis, 733–790
 - complete response to periodic forcing functions, 748–750, 786
 - complex form of Fourier series, 750–757, 787
 - sampling function, 754–757
 - computer-aided analysis, 774–777
 - definition of Fourier transform, 757–761, 788
 - Fourier transform of a general periodic time function, 769–770, 788–789
 - Fourier transform pairs for simple time functions, 764–767, 788
 - constant forcing function, 766
 - signum function, 766–767
 - unit-impulse function, 764–766
 - unit-step function, 767
 - Laplace transform, similarities to, 759
 - LTspice for, 774–777

- physical significance of system function, 777–779, 789–790
 - practical application: image processing, 780–781
 - properties of Fourier transform, 761–764, 788
 - physical significance of Fourier transform, 762–764
 - summary and review, 780–783
 - summary of some Fourier transform pairs, 768
 - symmetry, 743–747, 785
 - even and odd symmetry, 743
 - half-wave symmetry, 745–747
 - symmetry and Fourier series terms, 743–745
 - system function and response in frequency domain, 770–773, 789
 - trigonometric form of Fourier series, 733–743, 783–785
 - Fourier coefficients, evaluation of, 737–738
 - Fourier series, 735–736
 - harmonics, 734–735
 - line and phase spectra, 741–743
 - useful trigonometric integrals, 736–737
 - Frequencies, 329–330
 - complex frequency, 330
 - exponential damping coefficient, 329
 - neper frequency, 329
 - resonant frequency, 329
 - Frequency domain
 - differentiation in Laplace transform, 836–837
 - integration in Laplace transform, 837
 - Frequency limits in digital integrated circuits, 309–310
 - Frequency response, 4, 615–686
 - advanced filter design, 669–674, 685
 - Butterworth filters, 670–674
 - Chebyshev filters, 670–672, 674
 - Sallen-Key amplifier, 671–674
 - bandwidth and high- Q circuits, 640–646, 680–681
 - approximations for high- Q circuits, 642–646
 - bandwidth, 641–642
 - basic filter design, 660–669, 683–685
 - active filters, 666–667
 - bandpass filters, 663–666
 - passive low-pass and high-pass filters, 661–663
 - Bode diagrams, 618–632, 678–679
 - complex conjugate pairs, 627–629
 - computer-aided analysis, 630–632
 - decibel (dB) scale, 618–619
 - determination of asymptotes, 619–620
 - higher-order terms, 626–627
 - multiple terms, 620–621
 - phase response, 621–622
 - smoothing Bode plots, 620
 - linear circuit analysis, 4
 - other resonant forms, 649–656, 681–682
 - equivalent series and parallel combinations, 651–656
 - parallel resonance, 633–640, 679–680
 - damping factor, 639–640
 - quality factor (Q), 636–638
 - resonance, 633–635
 - resonance and the voltage response, 635–636
 - practical application: bass, treble, and midrange adjustment, 668–669
 - scaling, 657–660, 682–683
 - frequency scaling, 657–659
 - magnitude scaling, 657–659
 - series resonance, 646–649, 681
 - summary and review, 674–676
 - transfer function, 615–618, 676–678
 - Frequency scaling, 657–659
 - Frequency selectivity, 642
 - Frequency shifting
 - Laplace transform, 835–836
 - Fundamental frequency, 734–735
 - Fuses
 - Ohm's law, 30
- ## G
- Graphic equalizer, 668–669
 - Ground connections, 69–70
 - chassis ground, 69
 - earth ground, 69
 - signal ground, 69
- ## H
- h, z, y, and t** parameters, transformations between, 709
 - Half-power frequency, 619
 - Half-wave symmetry, 745–747
 - Fourier circuit analysis, 745–747
 - Harmonics, 734–735
 - Henry (H), 237
 - Henry, Joseph, 237
 - High-pass filters, 660–661
 - High- Q circuits, approximations for, 642–646
 - Hybrid parameters
 - two-port networks, 713–716, 728–730
 - Hybrid π model, 586
 - Hysteresis
 - comparators, 204
- ## I
- Ideal op amp, 186–195, 210, 219–221
 - computer-aided analysis, 194–195
 - difference amplifiers, 191–192
 - inverting amplifiers, 187–190, 192
 - noninverting amplifiers, 188–190, 192
 - practical application: fiber optic intercom, 193–194
 - rules, 187
 - summing amplifiers, 190–192, 195
 - voltage followers (unity gain amplifiers), 189–190, 192
 - Ideal transformers, 526–535, 542–543
 - equivalent circuits, 532–535
 - turns ratio, 526–528
 - use of transformers for current adjustment, 528–529
 - use of transformers for impedance matching, 528
 - use of transformers for voltage level adjustment, 529
 - voltage relationship in the time domain, 530, 532

- Image processing, Fourier-based techniques in, 780–781
 - Imaginary number, 817
 - Imaginary sources lead to imaginary responses, 389
 - Imaginary unit, 817
 - Immittance, 404
 - Impedance and admittance, 399–404, 424–425
 - admittance, 404
 - parameters, two-port networks, 692–699, 723–725
 - impedance
 - matching, 443–446, 528
 - parameters, two-port networks, 708–712, 727–728
 - parallel impedance combinations, 399–400
 - reactance, 400–404
 - series impedance combinations, 399
 - Independent current sources, 22
 - Independent voltage sources, 21–22
 - Inductors and capacitors, 229–272
 - capacitors, 229–237, 261–264
 - energy storage, 234–237
 - ideal capacitor model, 229–232, 237
 - integral voltage–current relationships, 232–234
 - computer modeling of circuits with capacitors and inductors, 257–259, 271–272
 - duality, 245, 254–257, 270–271
 - inductance and capacitance combinations, 247–250, 266–268
 - capacitors in parallel, 249–250
 - capacitors in series, 248–249
 - inductors in parallel, 248
 - inductors in series, 247–248
 - inductors, 237–246, 264–266, 396
 - energy storage, 243–245
 - ideal inductor model, 237–241, 245
 - integral voltage–current relationships, 241–243
 - linearity and its consequences, 250–252, 268–269
 - practical application: in search of the missing element (the memristor), 246
 - simple op amp circuits with capacitors, 252–253, 269–270
 - summary and review, 260–261
 - Input bias current, 211
 - Input offset voltage
 - operational amplifiers (OAs), 214
 - Instantaneous power, 432–434, 460, 462
 - not to be confused with average power, 438
 - power due to sinusoidal excitation, 433
 - Instrumentation amplifiers, 206–209
 - feedback, 206–209
 - practical application: electrocardiogram (ECG), 208–209
 - Integral voltage–current relationships
 - capacitors, 232–234
 - International System of Units (SI), 12
 - base units, 12–13
 - prefixes, 12–13
 - Introduction, 1–10
 - analysis and design, 6
 - computer-aided analysis, 6–9
 - frequency response, 4
 - linear circuit analysis, 2–4
 - nonlinear problems, 2–3
 - overview of text, 2–4
 - phasor analysis, 4
 - problem solving
 - art of, 1–2
 - strategies, successful, 9–10
 - relationship of circuit analysis to engineering, 5–6
 - “translating” relevant variables, 5
 - sinusoidal analysis, 4
 - transient analysis, 4
 - Inverse transform techniques, 554–560, 607–608
 - distinct poles and the method of residues, 557–558
 - inverse transform techniques for rational functions, 556–557
 - linearity theorem, 554–556
 - repeated poles, 558–560
 - Inverting amplifiers, 187–190, 192
 - Inverting input
 - operational amplifiers (OAs), 186
- ## J
- Joule (J), 12, 20
- ## K
- Kelvin, 12
 - Kilogram, 12
 - Kilowatt hour (kWh), 20, 451
 - Kirchhoff, Robert, 44
 - Kirchhoff's current law (KCL), 43–46, 72–74
 - Kirchhoff's voltage law (KVL), 43, 46–50, 74–76
 - Kirchoff's laws using phasors, 397–398
- ## L
- Lagging and leading, 382–383
 - Laplace transform
 - advanced theorems, 833–838
 - differentiation in frequency domain, 836–837
 - frequency shifting, 835–836
 - integration in frequency domain, 837
 - time-scaling theorem, 838
 - transforms of periodic time functions, 833–835
 - basic theorems, 561–568, 608–609
 - time differentiation theorem, 562
 - time-integration theorem, 564–565
 - time-shift theorem, 566–567
 - transforms of sinusoids, 566
 - defined, 549–552, 606
 - one-sided, 551–552
 - operations, 568
 - pairs, 567
 - similarities to Fourier transform, 759
 - simple time functions, 552–554, 606–607
 - exponential function e^{-st} , 553–554
 - ramp function $tu(t)$, 554
 - unit-impulse function $\delta(t - t_0)$, 553
 - unit-step function $u(t)$, 553
 - Line and phase spectra, 741–743
 - Linear circuit
 - analysis, 2–4
 - DC analysis, 4
 - frequency response, 4

- sinusoidal analysis, 4
 - transient analysis, 4
 - defined, 134
 - Linear dependent source, defined, 134
 - Linear element, defined, 133
 - Linearity
 - consequences, 250–252, 268–269
 - superposition and, 133–144, 171–173
 - Linear resistors, 26
 - Linear transformers, 519–526, 540–542
 - primary, 519
 - reflected impedance, 519–521
 - secondary, 519
 - T and Π equivalent networks, 521–524
 - Linear voltage–current relationship, 133–134
 - Line spectrum, 741–743
 - Line-to-line voltages, 479–484
 - Links, 792–793
 - network topology, 797–802
 - Loops
 - defined, 792
 - voltage and current laws, 44, 71–72
 - Lossless *LC* circuits, 365–368, 378–379
 - Low-pass filters, 660
 - LTspice, 111–113, 303–304
 - AC circuit power analysis, 449–451
 - bandpass filter design, 665
 - circuits in the sinusoidal steady state, analyzing, 414–415
 - circuits that contain magnetically coupled inductances, simulating, 524–526
 - circuits with capacitors and inductors, modeling, 257–259
 - dc parameter sweep, 141–143
 - Fourier-based analysis with, 774–777
 - mathematical operations on voltages and currents that result from a simulation, 349–351
 - op amp circuits
 - analyzing, 194–195
 - simulating, 215–217
 - sequentially switched circuits, 307–308
 - transient analysis, 280–281
 - tutorial, 813–817
 - Lumped-parameter network, 43
- ## M
- Magnetically coupled circuits, 507–544
 - computer-aided analysis, 524–526
 - energy considerations, 515–518, 540
 - coupling coefficient, 518
 - equality of M_{12} and M_{21} , 516–517
 - establishing an upper limit for M , 517
 - ideal transformers, 526–535, 542–543
 - equivalent circuits, 532–535
 - turns ratio, 526–528
 - use of transformers for current adjustment, 528–529
 - use of transformers for impedance matching, 528
 - use of transformers for voltage level adjustment, 529
 - voltage relationship in the time domain, 530, 532
 - linear transformers, 519–526, 540–542
 - primary, 519
 - reflected impedance, 519–521
 - secondary, 519
 - T and Π equivalent networks, 521–524
 - mutual inductance, 507–515, 536–539
 - coefficient of mutual inductance, 508
 - combined mutual and self-induction voltage, 510
 - dot convention, 509–515
 - practical application: superconducting transformers, 531–532
 - summary and review, 535–536
 - Magnetic flux, 507–508
 - Magnitude scaling, 657–659
 - MATLAB, 31–32, 90–91, 617
 - Bode diagrams, 630–632
 - characterization of two-port networks using transmission parameters, 719–720
 - s*-domain circuit analysis, 560–561, 577–579
 - tutorial, 827–832
 - generating plots, 830
 - getting started, 827–828
 - useful functions, 830
 - variables and mathematical operations, 828–829
 - writing programs, 830–832
 - Matrices, 804–806
 - Matrix inversion, 806–807
 - Maximum power transfer, 163–165, 179–181, 441–446, 464
 - average power delivered to load, 442–443
 - impedance matching, 443–446
 - theorem, 163
 - Memristor, 246
 - Mesh, defined, 101, 792
 - Mesh and nodal analysis, 4, 85–132
 - comparison of nodal versus mesh analysis, 109–111, 128–130
 - computer-aided circuit analysis, 111–114, 130
 - mesh analysis, 85, 99–109, 123–126
 - mesh current, 101–105
 - planar circuit, 100
 - procedure, summarized, 105–106
 - supermesh, 106–109, 126–128
 - nodal analysis, 85–99, 117–120
 - procedure, summarized, 95
 - reference node, 86–87
 - supernodes, 95–99, 120–123
 - practical application: node-based circuit definition, 114
 - summary and review, 114–117
 - Metal oxide semiconductor field effect transistor (MOSFET), 25
 - Meter, 12
 - Midrange, bass, and treble adjustment, 668–669
 - Mole, 12
 - Molecular beam epitaxy crystal growth facility, 5
 - Multiband filters, 661
 - Multiple-frequency circuits, 448–449
 - Multipoint networks, 687
 - Mutual inductance, 507–515, 536–539
 - coefficient of mutual inductance, 508
 - combined mutual and self-induction voltage, 510
 - dot convention, 509–515

- N**
- National Bureau of Standards, 11–12
 - Natural resonant frequency, 344
 - Natural response, 733–734
 - driven RC circuits, 294–295
 - source-free RC circuits, 274
 - Negative feedback, 199–201
 - Negative feedback path, 601
 - Negative phase sequence, 478
 - Negative power, 18
 - Néper frequency, 329, 546
 - Nepers (Np), 546
 - Networks, 24–25
 - defined, 24
 - topology, 791–802
 - links and loop analysis, 797–802
 - trees and general nodal analysis, 791–797
 - Nodal and mesh analysis, 4, 85–132
 - comparison of nodal versus mesh analysis, 109–111, 128–130
 - computer-aided circuit analysis, 111–114, 130
 - mesh analysis, 85, 99–109, 123–126
 - mesh, defined, 101
 - mesh current, 101–105
 - planar circuit, 100
 - procedure, summarized, 105–106
 - supermesh, 106–109, 126–128
 - nodal analysis, 85–99, 117–120
 - procedure, summarized, 95
 - reference node, 86–87
 - supernodes, 95–99, 120–123
 - practical application: node-based circuit definition, 114
 - in the s -domain, 576, 580–584, 610–612
 - sinusoidal steady-state analysis, 404–407, 425–427
 - summary and review, 114–117
 - Nodes
 - analysis. *See* Nodal and mesh analysis
 - defined, 791
 - voltage and current laws, 44, 71–72
 - distributed-parameter network, 43
 - lumped-parameter network, 43
 - Noninverting amplifiers, 188–190, 192
 - Noninverting input, 186
 - difference amplifiers, 191–192
 - inverting amplifiers, 187–190, 192
 - noninverting amplifiers, 188–190, 192
 - practical application: fiber optic intercom, 193–194
 - rules, 187
 - summing amplifiers, 190–192, 195
 - voltage followers (unity gain amplifiers), 189–190, 192
 - inverting input, 186
 - LTspice
 - analyzing, 194–195
 - simulating, 215–217
 - noninverting input, 186
 - practical considerations, 209–217, 226–227
 - common-mode rejection, 212
 - derivation of ideal op amp rules, 211–212
 - input offset voltage, 214
 - more detailed op amp model, 209–211
 - nonideality, 214
 - packaging, 214–215
 - saturation, 212–214
 - summary and review, 218–219
 - Ordinate, 657
 - Ørsted, Hans Christian, 237
 - Oscillation, 326–327
 - Oscillators, 601–603
 - Overdamped parallel RLC circuits, 331–339, 371–372
 - finding values for A_1 and A_2 , 332–336
 - graphical representation of the overdamped response, 336–338
 - Overdamped response, 330–331, 347, 353
- O**
- Octave, 619
 - Odd and even symmetry, 743
 - Fourier circuit analysis, 743
 - Ohm, Georg Simon, 25
 - Ohm's law, 25–33, 39–41, 395
 - conductance, 30–31
 - fuses, 30
 - power absorption, 26–27
 - practical application (wire gauge), 28–29
 - One-port networks, 687–692, 722–723
 - One-sided Laplace transform, definition of, 551–552
 - Open circuit
 - defined, 33
 - Operational amplifiers (OAs), 185–228
 - background, 185–186
 - cascaded stages, 195–199, 221–223
 - circuits with capacitors, 252–253, 269–270
 - computer-aided analysis, 215–217
 - defined, 186
 - feedback, comparators, and the instrumentation amplifier, 199–209, 223–226
 - comparators, 201–206
 - instrumentation amplifiers, 206–209
 - negative and positive feedback, 199–201
 - ideal op amp, 186–195, 210, 219–221
 - computer-aided analysis, 194–195
 - Nonlinear problems, 2–3
 - Nonperiodic functions, average power for, 440–441
 - Nonplanar circuit, defined, 792
 - Norton and Thévenin equivalent circuits, 4, 152–162, 176–179
 - key points, 155–156
 - Norton's theorem, 4, 156
 - procedure recap, 160, 162
 - Thévenin equivalent resistance, 155
 - Thévenin's theorem, 4, 154
 - when dependent sources are present, 158
 - Notch filters, 661
- P**
- p (power). *See* Power (p)
 - Packaging
 - operational amplifiers (OAs), 214–215
 - Parallel
 - capacitors, 249–250
 - defined, 53

- inductors, 248
 - transforming current source and resistor combination, 150
 - Parallel resonance, 633–640, 679–680
 - damping factor, 639–640
 - quality factor (Q), 636–638
 - voltage response and, 635–636
 - Parseval-Deschenes, Marc Antoine, 762
 - Passband, 661
 - Passive devices, 185
 - Passive low-pass and high-pass filters, 661–663
 - Passive sign convention, 18
 - Paths
 - defined, 791
 - voltage and current laws, 44, 71–72
 - Periodic time function, general
 - Fourier transform, 769–770, 788–789
 - Periodic time functions
 - Laplace transform, 833–835
 - Periodic waveforms
 - average power for, 435
 - effective values of current and voltage, 446–447
 - PF. *See* Power factor
 - Phase and line spectra, 741–743
 - Phase response
 - Bode diagrams, 621–622
 - Phase voltages, 478
 - Phasor analysis, 4
 - Phasor diagrams
 - sinusoidal steady-state analysis, 416–418, 429
 - Phasors, 393–398, 423–424
 - capacitors, 397
 - inductors, 396
 - Kirchoff's laws using phasors, 397–398
 - resistors, 395–396
 - Philbrick K2-W op amp, 185–186
 - Physically realizable systems, 591
 - Planar circuit, defined, 792
 - Polar form of complex numbers, 824–826
 - Poles of $F(s)$, 569
 - Poles of $V(s)$, 556
 - Polyphase circuits, 471–506
 - delta (Δ) connection, 484–487, 503–504
 - Δ -connected sources, 487, 490
 - polyphase systems, 472–474, 500–501
 - balanced load, 472
 - double-subscript notation, 473–474
 - power measurement in three-phase systems, 490–498, 504–505
 - two-wattmeter method, 495–498
 - wattmeter, use of, 490–492
 - wattmeter in a three phase system, 492–495
 - practical application: power-generating systems, 488–489
 - single-phase three-wire systems, 474–478, 501
 - effect of finite wire impedance, 475
 - term "single phase," 475
 - summary and review, 498–499
 - three-phase Y-Y connection, 478–484, 502–503
 - line-to-line voltages, 479–484
 - Port, defined, 687
 - Positive feedback, 199–201, 203, 601
 - Positive feedback configuration comparators, 203–204
 - Positive phase sequence, 478
 - Power (p), 17–19, 35–39
 - absorbed, 18, 26–27
 - negative, 18
 - passive sign convention, 18
 - supplied, 18
 - Power analysis, AC circuit. *See* AC circuit power analysis
 - Power factor (PF), 451–454, 460
 - angle, 452–454
 - apparent power and, 451–455, 466
 - correction, 457–458
 - Power-generating systems, 488–489
 - Power measurement, 456
 - Power triangle, 456
 - Practical current sources, 146
 - Practical voltage sources, 144–145
 - Primary transformers, 519
 - Problem solving
 - art of, 1–2
 - strategies, successful, 9–10
 - testing the solution, 9
 - Pulse waveforms using unit-step functions, 303–304
- ## Q
- Quadrature component, 456
 - Quadrature power, 456
 - Quality factor (Q), 636–638
- ## R
- Ramp function $tu(t)$
 - Laplace transform of simple time functions, 554
 - Rational functions, 556
 - Rationalizing the denominator, 820
 - RC and RL circuits, basic, 273–324
 - computer-aided analysis, 280–281
 - driven RC circuits, 294–300, 319–321
 - complete response, determination of, 295–297
 - developing an intuitive understanding, 300
 - forced response, 295
 - natural response, 294–295
 - driven RL circuits, 300–302, 321–322
 - exponential response, properties of, 277–281, 314–315
 - time constant, 278–280
 - general perspective, 285–290, 316–318
 - initial conditions: $t = 0^+$ and $t = 0^-$, 286–290
 - source-free RC and RL circuit with single energy storage element, 286
 - practical application: frequency limits in digital integrated circuits, 309–310
 - predicting the response of sequentially switched circuits, 303–311, 323
 - I: time enough to fully charge and fully discharge, 304–305
 - II: time enough to fully charge but not fully discharge, 306
 - III: no time to fully charge but time to fully discharge, 306

- RC* and *RL* circuits, basic (*Continued*)
- IV: no time to fully charge or even fully discharge, 306–308
 - source-free *RC* circuits, 273–277, 313–314
 - energy, accounting for, 277
 - forced response, 274
 - general solution approach, 275–277
 - natural response, 274
 - solution by direct integration, 272–273
 - steady-state response, 274
 - transient response, 274
 - source-free *RL* circuit, 281–285, 315–316
 - summary and review, 311–312
 - time-varying forced response, 310–311
 - unit-step function, 290–294, 318–319
 - physical sources and the unit-step function, 292
 - rectangular pulse function, 293–294
 - singularity functions, 291
- Reactive power, 454–455, 460
- Real component, 817
- Real part, 817
- Rectangular pulse function, 293–294
- Rectifiers, 472–473
- Reflected impedance
- transformers, 519–521
- Resistors, 395–396
- packages, 26
 - in series and parallel, 59–65, 79–81
- Resonance, 633–635
- voltage response and, 635–636
- Resonant frequency, 329
- Ripple constant, 670
- RL* and *RC* circuits, basic, 273–324
- computer-aided analysis, 280–281
 - driven *RC* circuits, 294–300, 319–321
 - complete response, determination of, 295–297
 - developing an intuitive understanding, 300
 - forced response, 295
 - natural response, 294–295
 - driven *RL* circuits, 300–302, 321–322
 - exponential response, properties of, 277–281, 314–315
 - time constant, 278–280
 - general perspective, 285–290, 316–318
 - initial conditions: $t = 0^+$ and $t = 0^-$, 286–290
 - source-free *RC* and *RL* circuit with single energy storage element, 286
 - practical application: frequency limits in digital integrated circuits, 309–310
 - predicting the response of sequentially switched circuits, 303–311, 323
 - I: time enough to fully charge and fully discharge, 304–305
 - II: time enough to fully charge but not fully discharge, 306
 - III: no time to fully charge but time to fully discharge, 306
 - IV: no time to fully charge or even fully discharge, 306–308
 - source-free *RC* circuits, 273–277, 313–314
 - energy, accounting for, 277
 - forced response, 274
 - general solution approach, 275–277
 - natural response, 274
 - solution by direct integration, 272–273
 - steady-state response, 274
 - transient response, 274
 - source-free *RL* circuit, 281–285, 315–316
 - summary and review, 311–312
 - time-varying forced response, 310–311
 - unit-step function, 290–294, 318–319
 - physical sources and the unit-step function, 292
 - rectangular pulse function, 293–294
 - singularity functions, 291
- RLC* circuit, 325–380
- complete response of, 357–365, 376–378
 - summary, 357, 363–365
 - computer-aided analysis, 349–351
 - critical damping, 339–343, 372–373
 - finding values for A_1 and A_2 , 340–341
 - form of a critically damped response, 340
 - graphical representation of critically damped response, 341–343
 - forced response, 326, 357–358, 363, 365
 - lossless *LC* circuits, 365–368, 378–379
 - natural response, 325–332, 351, 357–358, 363, 365
 - overdamped parallel *RLC* circuits, 331–339, 371–372
 - finding values for A_1 and A_2 , 332–336
 - graphical representation of the overdamped response, 336–338
 - practical application: automated defibrillators, 364
 - source-free parallel circuits, 325–331, 370–371
 - definition of frequency terms, 329–330
 - obtaining the differential equation for a parallel *RLC* circuit, 327–328
 - physical intuition, 326–327
 - solution of the differential equation, 328–329
 - source-free series *RLC* circuits, 351–357, 375–376
 - series circuit response, 352–357
 - summary and review, 369–370
 - underdamped parallel *RLC* circuits, 343–351, 373–375
 - finding values for B_1 and B_2 , 345
 - form of the underdamped response, 344–345
 - graphical representation of underdamped response, 345–346
 - role of finite resistance, 346–347

- Robotic manipulator, 6
- Root-mean-square (RMS) value,
447–448
used to compute average power, 448
- S**
- Sallen-Key amplifier, 671–674
- Sampling function
complex form of Fourier series,
754–757
- Saturation, 200
operational amplifiers (OAs),
212–214
- Scales and units, 11–13, 34–35
- Scaling, 657–660, 682–683
frequency scaling, 657–659
magnitude scaling, 657–659
- Schmitt trigger
comparators, 204–206
- Scientific calculators, 803–804
- s*-domain circuit analysis, 545–614
complex frequency, 545–549, 606
DC case, 547
exponential case, 547
exponentially damped sinusoidal
case, 548
general form, 546–547
neper frequency, 546
relationship of *s* to reality,
548–549
sinusoidal case, 547
computer-aided analysis, 560–561,
577–579
convolution, 589–598, 613–614
convolution and realizable
systems, 591–592
convolution integral, 591
graphical method of convolution,
592–593
impulse response, 590–591
Laplace transform and, 595–596
transfer functions, further
comments on, 597
element representations in the time
and frequency domains,
summary of, 577
initial-value and final-value
theorems, 568–570, 609
final-value theorem, 569–570
initial value theorem, 568–569
- inverse transform techniques,
554–560, 607–608
distinct poles and the method of
residues, 557–558
inverse transform techniques for
rational functions, 556–557
linearity theorem, 554–556
repeated poles, 558–560
- Laplace transform, definition of,
549–552, 606
- Laplace transform of simple time
functions, 552–554,
606–607
exponential function e^{-at} , 553–554
ramp function $tu(t)$, 554
unit-impulse function $\delta(t - t_0)$,
553
unit-step function $u(t)$, 553
- nodal and mesh analysis in the
s-domain, 576, 580–584,
610–612
- poles, zeros, and transfer functions,
587–589, 613
pole-zero constellations, 588–589
- practical application: design of
oscillator circuits, 601–603
- summary and review, 603–605
- technique for synthesizing voltage
ratio $H(s) = V_{out}/V_{in}$,
599–600, 614
- using MATLAB, 560–561, 577–579
- $Z(s)$ and $Y(s)$, 571–576, 609–610
inductors in the frequency
domain, 571–572
modeling capacitors in the
s-domain, 574–575
modeling inductors in the
s-domain, 572–574
resistors in the frequency domain,
571
- Second, 12
- Secondary transformers, 519
- Sequentially switched circuits
LTspice, 307–308
predicting the response of, 303–311,
323
I: time enough to fully charge and
fully discharge, 304–305
II: time enough to fully charge but
not fully discharge, 306
III: no time to fully charge but
time to fully discharge, 306
IV: no time to fully charge or even
fully discharge, 306–308
- Series
capacitors, 248–249
circuit response, 352–357
inductors, 247–248
resonance, 646–649, 681
transforming a voltage source, 150
- Series and parallel connected sources,
55–59, 78–79
- Settling time, 337
- Short circuit, defined, 33
- Short-circuit admittance parameters,
694–695
- Short-circuit input admittance,
693–694
- Short-circuit output admittance,
694–695
- Short-circuit transfer admittances,
694–695
- SI (International System of Units)
prefixes, 12–13
- Sifting property, 553
- Signal ground, 69
- Signum function, 766–767
- Simple time functions
Fourier transform pairs for, 764–767,
788
constant forcing function, 766
signum function, 766–767
unit-impulse function, 764–766
unit-step function, 767
- Simultaneous equations, solution of,
803–810
Cramer's rule, 809–810
determinants, 807–809
matrices, 804–806
matrix inversion, 806–807
scientific calculators, 803–804
- Single-loop circuits, 50–53, 76–77
- Single-node-pair circuits, 53–55,
77–78
- Single-phase three-wire systems,
474–478, 501
effect of finite wire impedance, 475
term "single phase," 475
- Singularity functions, 291
- Sinusoidal current (ac), 15

- Sinusoidal analysis, 4
 - linear circuit analysis, 4
- Sinusoidal excitation, instantaneous power due to, 433
- Sinusoidal steady state, average power in, 435–436
- Sinusoidal steady-state analysis, 381–430
 - characteristics of sinusoids, 381–384, 420–421
 - converting sines to cosines, 383–384
 - lagging and leading, 382–383
- complex forcing function, 388–392, 422–423
 - algebraic alternative to differential equations, 390–391
 - applying, 389–390
 - imaginary sources lead to imaginary responses, 389
- computer-aided analysis, 414–415
- forced response to sinusoidal functions, 384–387, 421–422
 - compact and user-friendly form, 385–386
 - steady-state response, 384–385
- impedance and admittance, 399–404, 424–425
 - admittance, 404
 - parallel impedance combinations, 399–400
 - reactance, 400–404
 - series impedance combinations, 399
- nodal and mesh analysis, 404–407, 425–427
- phasor diagrams, 416–418, 429
- phasors, 393–398, 423–424
 - capacitors, 397
 - inductors, 396
 - Kirchoff's laws using phasors, 397–398
 - resistors, 395–396
- practical application: cutoff frequency of transistor amplifier, 408–409
- summary and review, 419–420
- superposition, source transformations, and Thévenin's theorem, 407–414, 427–428
- Sinusoidal waveform
 - effective (RMS) value of, 447–448
- Source-free parallel circuits, 325–331, 370–371
 - definition of frequency terms, 329–330
 - obtaining the differential equation for a parallel *RLC* circuit, 327–328
 - physical intuition, 326–327
 - solution of the differential equation, 328–329
- Source-free *RC* circuits, 273–277, 313–314
 - energy, accounting for, 277
 - forced response, 274
 - general solution approach, 275–277
 - natural response, 274
 - solution by direct integration, 272–273
 - steady-state response, 274
 - transient response, 274
- Source-free *RL* circuits, 281–285, 315–316
- Source-free series *RLC* circuits, 351–357, 375–376
 - series circuit response, 352–357
- Source transformations, 4, 144–151, 173–176, 407–414, 427–428
 - equivalent practical sources, 146–147
 - key points, 150–151
 - practical current sources, 146
 - practical voltage sources, 144–145
 - procedure, summarized, 151
- Space shuttle design, 6
- SPICE (Simulation Program with Integrated Circuit Emphasis), 111–113, 303–304
 - AC circuit power analysis, 449–451
 - bandpass filter design, 665
 - circuits including dependent source, simulating, 356
 - circuits in the sinusoidal steady state, analyzing, 414–415
 - circuits that contain magnetically coupled inductances, simulating, 524–526
 - circuits with capacitors and inductors, modeling, 257–259
 - comparator circuit, simulating, 201–202
 - dc parameter sweep, 141–143
 - Fourier-based analysis with, 774–777
 - mathematical operations on voltage and currents that result from a simulation, 349–350
 - op amp circuits
 - analyzing, 194–195
 - simulating, 215–217
 - sequentially switched circuits, 307–308
 - transient analysis, 280–283
 - tutorial, 813–817
 - Wien-bridge oscillator, designing, 601–603
- Square matrix, 804
- Stable state, 200
- Steady-state response
 - source-free *RC* circuits, 274
- Stopband, 661
- Strukov, Dmitri, 246
- Summing amplifiers, 190–192, 195
- Superconducting transformers, 531–532
- Supermesh, 106–109, 126–128
- Supernodes, 95–99, 120–123
 - analysis procedure, summarized, 97–98
- Superposition, 4, 134–136, 407–414, 427–428
 - defined, 133
 - limits of, 143–144
 - procedure, summarized, 140
 - theorem, 135
- Supplied power, 18
- Susceptance, 404
- Symmetry
 - Fourier circuit analysis, 743–747, 785
 - even and odd symmetry, 743
 - half-wave symmetry, 745–747
 - symmetry and Fourier series terms, 743–745
- System function, 589

T

- t, z, h, and y parameters, transformations between, 709
- T and Π equivalent networks, 521–524
- Tesla, Nikola, 471
- Testing the solution, 9
- Thévenin and Norton equivalent circuits, 4, 152–162, 176–179
 - key points, 155–156
 - Norton's theorem, 4, 156
 - procedure recap, 160, 162
 - Thévenin equivalent circuit, 288
 - Thévenin equivalent resistance, 155
 - Thévenin's theorem, 4, 154, 407–414, 427–428
 - proof of, 811–812
 - when dependent sources are present, 158
- Three-phase systems, power measurement in, 490–498, 504–505
 - two-wattmeter method, 495–498
 - wattmeter, use of, 490–492
 - wattmeter in a three phase system, 492–495
- Three-phase Y-Y connection, 478–484, 502–503
 - line-to-line voltages, 479–484
- Time-domain and frequency-domain voltage-current expressions, comparison of, 397
- Time-scaling theorem
 - Laplace transform, 838
- Time-varying forced response, 310–311
 - RC and RL circuits, basic, 310–311
- Topology, defined, 791
- Transfer function, 587–588, 615–618, 676–678
 - $H(j\omega)$, 616
 - $H(s)$, 616
- Transformers, 507
 - step-down transformers, 529
 - step-up transformers, 529
- Transient analysis, 4
 - linear circuit analysis, 4
 - LTspice, 280–281
- Transient response
 - source-free RC circuits, 274

Transmission parameters

- two-port networks, 716–720, 730–731
 - computer-aided analysis, 719–720
- Treble, bass, and midrange adjustment, 668–669
- Trees, 792–793
- Trigonometric form of Fourier series, 733–743, 783–785
 - Fourier coefficients, evaluation of, 737–738
 - Fourier series, 735–736
- Turns ratio, 526–528
- Two-port networks, 687–732
 - admittance parameters, 692–699, 723–725
 - matrix notation, 693
 - equivalent networks, 699–707, 725–727
 - hybrid parameters, 713–716, 728–730
 - impedance parameters, 708–712, 727–728
 - one-port networks, 687–692, 722–723
 - practical application: characterizing transistors, 715–716
 - summary and review, 720–721
 - transmission parameters, 716–720, 730–731
 - computer-aided analysis, 719–720
- Two-wattmeter method, 495–498

U

- Underdamped parallel RLC circuits, 343–351, 373–375
 - finding values for B_1 and B_2 , 345
 - form of the underdamped response, 344–345
 - graphical representation of underdamped response, 345–346
 - role of finite resistance, 346–347
- Underdamped response, 330–331, 343, 347, 353
- Unit-impulse function, 291
 - Fourier transform pairs for, 764–766

Unit-impulse function $\delta(t - t_0)$

- Laplace transform of simple time functions, 553
- Units and scales, 11–13, 34–35
- Unit-step function, 290–294, 318–319
 - fourier transform pairs for, 767
 - physical sources and the unit-step function, 292
 - rectangular pulse function, 293–294
 - singularity functions, 291
- Unity gain amplifiers (voltage followers), 189–190, 192
- Unstable runaway state, 200

V

- VA (volt-ampere), 452
- VAR (volt-ampere-reactive), 455
- Vector, 91, 804
- Voltage, 16, 35–39
 - defined, 16
- Voltage and current, effective values of, 446–451, 464–465
- Voltage and current laws, 43–84
 - branches, 44, 71–72
 - Kirchhoff's current law (KCL), 43–46, 72–74
 - Kirchhoff's voltage law (KVL), 43, 46–50, 74–76
 - loops, 44, 71–72
 - nodes, 44, 71–72
 - distributed-parameter network, 43
 - lumped-parameter network, 43
 - paths, 44, 71–72
 - practical application: ground connections, 69–70
 - chassis ground, 69
 - earth ground, 69
 - signal ground, 69
 - resistors in series and parallel, 59–65, 79–81
 - series and parallel connected sources, 55–59, 78–79
 - single-loop circuits, 50–53, 76–77
 - single-node-pair circuits, 53–55, 77–78
 - summary and review, 70–71
 - voltage and current division, 65–68, 81–82

Voltage and current sources, 20–25, 39
 dependent sources, 22–23
 independent current sources, 22
 independent voltage sources, 21–22
 networks and circuits, 24–25
Voltage followers (unity gain amplifiers),
 189–190, 192
Voltage level adjustment, use of
 transformers for, 529
Voltages and currents that result from a
 simulation, mathematical
 operations on
 LTspice, 349–351
Volt-ampere-reactive (VAR), 455
Volt-amperes (VA), 452

W

Watt (W), 12
Watt hours (Wh), 20
Wattmeters
 in three phase system, 492–495
 two-wattmeter method, 495–498
 use of, 490–492
Westinghouse, George, 471
Wien-bridge oscillator, 601
Wire gauges and resistance of solid
 copper wire, 29

Y

y, z, h, and t parameters, transformations
 between, 709

Z

z, y, h, and t parameters, transformations
 between, 709
Z(s) and **Y(s)**, 571–576, 609–610
 inductors in the frequency domain,
 571–572
 modeling capacitors in the *s*-domain,
 574–575
 modeling inductors in the *s*-domain,
 572–574
 resistors in the frequency domain,
 571
Zeros of **V(s)**, 556