

CONTENTS

| | | | |
|---|--|--|----|
| List of Tables | xxii | | |
| Preface to the First Edition | xxv | | |
| Preface to the Second Edition | xxvii | | |
| Preface to the Third Edition | xxix | | |
| ONE: Foundations | 1 | | |
| 1.1 Introduction | 1 | | |
| 1.2 Voltage, current, and resistance | 1 | | |
| 1.2.1 Voltage and current | 1 | | |
| 1.2.2 Relationship between voltage and current: resistors | 3 | | |
| 1.2.3 Voltage dividers | 7 | | |
| 1.2.4 Voltage sources and current sources | 8 | | |
| 1.2.5 Thévenin equivalent circuit | 9 | | |
| 1.2.6 Small-signal resistance | 12 | | |
| 1.2.7 An example: “It’s too hot!” | 13 | | |
| 1.3 Signals | 13 | | |
| 1.3.1 Sinusoidal signals | 14 | | |
| 1.3.2 Signal amplitudes and decibels | 14 | | |
| 1.3.3 Other signals | 15 | | |
| 1.3.4 Logic levels | 17 | | |
| 1.3.5 Signal sources | 17 | | |
| 1.4 Capacitors and ac circuits | 18 | | |
| 1.4.1 Capacitors | 18 | | |
| 1.4.2 <i>RC</i> circuits: <i>V</i> and <i>I</i> versus time | 21 | | |
| 1.4.3 Differentiators | 25 | | |
| 1.4.4 Integrators | 26 | | |
| 1.4.5 Not quite perfect. . . | 28 | | |
| 1.5 Inductors and transformers | 28 | | |
| 1.5.1 Inductors | 28 | | |
| 1.5.2 Transformers | 30 | | |
| 1.6 Diodes and diode circuits | 31 | | |
| 1.6.1 Diodes | 31 | | |
| 1.6.2 Rectification | 31 | | |
| 1.6.3 Power-supply filtering | 32 | | |
| 1.6.4 Rectifier configurations for power supplies | 33 | | |
| | | 1.6.5 Regulators | 34 |
| | | 1.6.6 Circuit applications of diodes | 35 |
| | | 1.6.7 Inductive loads and diode protection | 38 |
| | | 1.6.8 Interlude: inductors as friends | 39 |
| | 1.7 Impedance and reactance | | 40 |
| | 1.7.1 Frequency analysis of reactive circuits | | 41 |
| | 1.7.2 Reactance of inductors | | 44 |
| | 1.7.3 Voltages and currents as complex numbers | | 44 |
| | 1.7.4 Reactance of capacitors and inductors | | 45 |
| | 1.7.5 Ohm’s law generalized | | 46 |
| | 1.7.6 Power in reactive circuits | | 47 |
| | 1.7.7 Voltage dividers generalized | | 48 |
| | 1.7.8 <i>RC</i> highpass filters | | 48 |
| | 1.7.9 <i>RC</i> lowpass filters | | 50 |
| | 1.7.10 <i>RC</i> differentiators and integrators in the frequency domain | | 51 |
| | 1.7.11 Inductors versus capacitors | | 51 |
| | 1.7.12 Phasor diagrams | | 51 |
| | 1.7.13 “Poles” and decibels per octave | | 52 |
| | 1.7.14 Resonant circuits | | 52 |
| | 1.7.15 <i>LC</i> filters | | 54 |
| | 1.7.16 Other capacitor applications | | 54 |
| | 1.7.17 Thévenin’s theorem generalized | | 55 |
| | 1.8 Putting it all together – an AM radio | | 55 |
| | 1.9 Other passive components | | 56 |
| | 1.9.1 Electromechanical devices: switches | | 56 |
| | 1.9.2 Electromechanical devices: relays | | 59 |
| | 1.9.3 Connectors | | 59 |
| | 1.9.4 Indicators | | 61 |
| | 1.9.5 Variable components | | 63 |
| | 1.10 A parting shot: confusing markings and itty-bitty components | | 64 |
| | 1.10.1 Surface-mount technology: the joy and the pain | | 65 |

| | | | |
|--|-----------|---|------------|
| Additional Exercises for Chapter 1 | 66 | 2.6.1 Regulated power supply | 123 |
| Review of Chapter 1 | 68 | 2.6.2 Temperature controller | 123 |
| | | 2.6.3 Simple logic with transistors and diodes | 123 |
| TWO: Bipolar Transistors | 71 | Additional Exercises for Chapter 2 | 124 |
| 2.1 Introduction | 71 | Review of Chapter 2 | 126 |
| 2.1.1 First transistor model: current amplifier | 72 | THREE: Field-Effect Transistors | 131 |
| 2.2 Some basic transistor circuits | 73 | 3.1 Introduction | 131 |
| 2.2.1 Transistor switch | 73 | 3.1.1 FET characteristics | 131 |
| 2.2.2 Switching circuit examples | 75 | 3.1.2 FET types | 134 |
| 2.2.3 Emitter follower | 79 | 3.1.3 Universal FET characteristics | 136 |
| 2.2.4 Emitter followers as voltage regulators | 82 | 3.1.4 FET drain characteristics | 137 |
| 2.2.5 Emitter follower biasing | 83 | 3.1.5 Manufacturing spread of FET characteristics | 138 |
| 2.2.6 Current source | 85 | 3.1.6 Basic FET circuits | 140 |
| 2.2.7 Common-emitter amplifier | 87 | 3.2 FET linear circuits | 141 |
| 2.2.8 Unity-gain phase splitter | 88 | 3.2.1 Some representative JFETs: a brief tour | 141 |
| 2.2.9 Transconductance | 89 | 3.2.2 JFET current sources | 142 |
| 2.3 Ebers–Moll model applied to basic tran- sistor circuits | 90 | 3.2.3 FET amplifiers | 146 |
| 2.3.1 Improved transistor model: transconductance amplifier | 90 | 3.2.4 Differential amplifiers | 152 |
| 2.3.2 Consequences of the Ebers–Moll model: rules of thumb for transistor design | 91 | 3.2.5 Oscillators | 155 |
| 2.3.3 The emitter follower revisited | 93 | 3.2.6 Source followers | 156 |
| 2.3.4 The common-emitter amplifier revisited | 93 | 3.2.7 FETs as variable resistors | 161 |
| 2.3.5 Biasing the common-emitter amplifier | 96 | 3.2.8 FET gate current | 163 |
| 2.3.6 An aside: the perfect transistor | 99 | 3.3 A closer look at JFETs | 165 |
| 2.3.7 Current mirrors | 101 | 3.3.1 Drain current versus gate voltage | 165 |
| 2.3.8 Differential amplifiers | 102 | 3.3.2 Drain current versus drain-source voltage: output conductance | 166 |
| 2.4 Some amplifier building blocks | 105 | 3.3.3 Transconductance versus drain current | 168 |
| 2.4.1 Push–pull output stages | 106 | 3.3.4 Transconductance versus drain voltage | 170 |
| 2.4.2 Darlington connection | 109 | 3.3.5 JFET capacitance | 170 |
| 2.4.3 Bootstrapping | 111 | 3.3.6 Why JFET (versus MOSFET) amplifiers? | 170 |
| 2.4.4 Current sharing in paralleled BJTs | 112 | 3.4 FET switches | 171 |
| 2.4.5 Capacitance and Miller effect | 113 | 3.4.1 FET analog switches | 171 |
| 2.4.6 Field-effect transistors | 115 | 3.4.2 Limitations of FET switches | 174 |
| 2.5 Negative feedback | 115 | 3.4.3 Some FET analog switch examples | 182 |
| 2.5.1 Introduction to feedback | 116 | 3.4.4 MOSFET logic switches | 184 |
| 2.5.2 Gain equation | 116 | 3.5 Power MOSFETs | 187 |
| 2.5.3 Effects of feedback on amplifier circuits | 117 | 3.5.1 High impedance, thermal stability | 187 |
| 2.5.4 Two important details | 120 | 3.5.2 Power MOSFET switching parameters | 192 |
| 2.5.5 Two examples of transistor amplifiers with feedback | 121 | | |
| 2.6 Some typical transistor circuits | 123 | | |

| | | | | | |
|-------------------------------------|---|------------|------------------------------------|---|------------|
| 3.5.3 | Power switching from logic levels | 192 | 4.5 | A detailed look at selected op-amp circuits | 254 |
| 3.5.4 | Power switching cautions | 196 | 4.5.1 | Active peak detector | 254 |
| 3.5.5 | MOSFETs versus BJTs as high-current switches | 201 | 4.5.2 | Sample-and-hold | 256 |
| 3.5.6 | Some power MOSFET circuit examples | 202 | 4.5.3 | Active clamp | 257 |
| 3.5.7 | IGBTs and other power semiconductors | 207 | 4.5.4 | Absolute-value circuit | 257 |
| 3.6 | MOSFETs in linear applications | 208 | 4.5.5 | A closer look at the integrator | 257 |
| 3.6.1 | High-voltage piezo amplifier | 208 | 4.5.6 | A circuit cure for FET leakage | 259 |
| 3.6.2 | Some depletion-mode circuits | 209 | 4.5.7 | Differentiators | 260 |
| 3.6.3 | Paralleling MOSFETs | 212 | 4.6 | Op-amp operation with a single power supply | 261 |
| 3.6.4 | Thermal runaway | 214 | 4.6.1 | Biasing single-supply ac amplifiers | 261 |
| Review of Chapter 3 | | 219 | 4.6.2 | Capacitive loads | 264 |
| FOUR: Operational Amplifiers | | 223 | 4.6.3 | “Single-supply” op-amps | 265 |
| 4.1 | Introduction to op-amps – the “perfect component” | 223 | 4.6.4 | Example: voltage-controlled oscillator | 267 |
| 4.1.1 | Feedback and op-amps | 223 | 4.6.5 | VCO implementation: through-hole versus surface-mount | 268 |
| 4.1.2 | Operational amplifiers | 224 | 4.6.6 | Zero-crossing detector | 269 |
| 4.1.3 | The golden rules | 225 | 4.6.7 | An op-amp table | 270 |
| 4.2 | Basic op-amp circuits | 225 | 4.7 | Other amplifiers and op-amp types | 270 |
| 4.2.1 | Inverting amplifier | 225 | 4.8 | Some typical op-amp circuits | 274 |
| 4.2.2 | Noninverting amplifier | 226 | 4.8.1 | General-purpose lab amplifier | 274 |
| 4.2.3 | Follower | 227 | 4.8.2 | Stuck-node tracer | 276 |
| 4.2.4 | Difference amplifier | 227 | 4.8.3 | Load-current-sensing circuit | 277 |
| 4.2.5 | Current sources | 228 | 4.8.4 | Integrating suntan monitor | 278 |
| 4.2.6 | Integrators | 230 | 4.9 | Feedback amplifier frequency compensation | 280 |
| 4.2.7 | Basic cautions for op-amp circuits | 231 | 4.9.1 | Gain and phase shift versus frequency | 281 |
| 4.3 | An op-amp smorgasbord | 232 | 4.9.2 | Amplifier compensation methods | 282 |
| 4.3.1 | Linear circuits | 232 | 4.9.3 | Frequency response of the feedback network | 284 |
| 4.3.2 | Nonlinear circuits | 236 | Additional Exercises for Chapter 4 | | 287 |
| 4.3.3 | Op-amp application: triangle-wave oscillator | 239 | Review of Chapter 4 | | 288 |
| 4.3.4 | Op-amp application: pinch-off voltage tester | 240 | FIVE: Precision Circuits | | 292 |
| 4.3.5 | Programmable pulse-width generator | 241 | 5.1 | Precision op-amp design techniques | 292 |
| 4.3.6 | Active lowpass filter | 241 | 5.1.1 | Precision versus dynamic range | 292 |
| 4.4 | A detailed look at op-amp behavior | 242 | 5.1.2 | Error budget | 293 |
| 4.4.1 | Departure from ideal op-amp performance | 243 | 5.2 | An example: the millivoltmeter, revisited | 293 |
| 4.4.2 | Effects of op-amp limitations on circuit behavior | 249 | 5.2.1 | The challenge: 10 mV, 1%, 10 M Ω , 1.8 V single supply | 293 |
| 4.4.3 | Example: sensitive millivoltmeter | 253 | 5.2.2 | The solution: precision RRIO current source | 294 |
| 4.4.4 | Bandwidth and the op-amp current source | 254 | 5.3 | The lessons: error budget, unspecified parameters | 295 |

| | | | | | | |
|------|---|---|--------|--|--|-----|
| 5.4 | Another example: precision amplifier with null offset | 297 | 5.11.3 | Selecting an auto-zero op-amp | 338 | |
| | 5.4.1 | Circuit description | 297 | 5.11.4 | Auto-zero miscellany | 340 |
| 5.5 | A precision-design error budget | 298 | 5.12 | Designs by the masters: Agilent's accurate DMMs | 342 | |
| | 5.5.1 | Error budget | 299 | 5.12.1 | It's <i>impossible!</i> | 342 |
| 5.6 | Component errors | 299 | 5.12.2 | Wrong – it <i>is</i> possible! | 342 | |
| | 5.6.1 | Gain-setting resistors | 300 | 5.12.3 | Block diagram: a simple plan | 343 |
| | 5.6.2 | The holding capacitor | 300 | 5.12.4 | The 34401A 6.5-digit front end | 343 |
| | 5.6.3 | Nulling switch | 300 | 5.12.5 | The 34420A 7.5-digit frontend | 344 |
| 5.7 | Amplifier input errors | 301 | 5.13 | Difference, differential, and instrumentation amplifiers: introduction | 347 | |
| | 5.7.1 | Input impedance | 302 | 5.14 | Difference amplifier | 348 |
| | 5.7.2 | Input bias current | 302 | 5.14.1 | Basic circuit operation | 348 |
| | 5.7.3 | Voltage offset | 304 | 5.14.2 | Some applications | 349 |
| | 5.7.4 | Common-mode rejection | 305 | 5.14.3 | Performance parameters | 352 |
| | 5.7.5 | Power-supply rejection | 306 | 5.14.4 | Circuit variations | 355 |
| | 5.7.6 | Nulling amplifier: input errors | 306 | 5.15 | Instrumentation amplifier | 356 |
| 5.8 | Amplifier output errors | 307 | 5.15.1 | A first (but naive) guess | 357 | |
| | 5.8.1 | Slew rate: general considerations | 307 | 5.15.2 | Classic three-op-amp instrumentation amplifier | 357 |
| | 5.8.2 | Bandwidth and settling time | 308 | 5.15.3 | Input-stage considerations | 358 |
| | 5.8.3 | Crossover distortion and output impedance | 309 | 5.15.4 | A “roll-your-own” instrumentation amplifier | 359 |
| | 5.8.4 | Unity-gain power buffers | 311 | 5.15.5 | A riff on robust input protection | 362 |
| | 5.8.5 | Gain error | 312 | 5.16 | Instrumentation amplifier miscellany | 362 |
| | 5.8.6 | Gain nonlinearity | 312 | 5.16.1 | Input current and noise | 362 |
| | 5.8.7 | Phase error and “active compensation” | 314 | 5.16.2 | Common-mode rejection | 364 |
| 5.9 | RRIO op-amps: the good, the bad, and the ugly | 315 | 5.16.3 | Source impedance and CMRR | 365 | |
| | 5.9.1 | Input issues | 316 | 5.16.4 | EMI and input protection | 365 |
| | 5.9.2 | Output issues | 316 | 5.16.5 | Offset and CMRR trimming | 366 |
| 5.10 | Choosing a precision op-amp | 319 | 5.16.6 | Sensing at the load | 366 | |
| | 5.10.1 | “Seven precision op-amps” | 319 | 5.16.7 | Input bias path | 366 |
| | 5.10.2 | Number per package | 322 | 5.16.8 | Output voltage range | 366 |
| | 5.10.3 | Supply voltage, signal range | 322 | 5.16.9 | Application example: current source | 367 |
| | 5.10.4 | Single-supply operation | 322 | 5.16.10 | Other configurations | 368 |
| | 5.10.5 | Offset voltage | 323 | 5.16.11 | Chopper and auto-zero instrumentation amplifiers | 370 |
| | 5.10.6 | Voltage noise | 323 | 5.16.12 | Programmable gain instrumentation amplifiers | 370 |
| | 5.10.7 | Bias current | 325 | 5.16.13 | Generating a differential output | 372 |
| | 5.10.8 | Current noise | 326 | 5.17 | Fully differential amplifiers | 373 |
| | 5.10.9 | CMRR and PSRR | 328 | 5.17.1 | Differential amplifiers: basic concepts | 374 |
| | 5.10.10 | GBW, f_T , slew rate and “ m ,” and settling time | 328 | 5.17.2 | Differential amplifier application example: wideband analog link | 380 |
| | 5.10.11 | Distortion | 329 | 5.17.3 | Differential-input ADCs | 380 |
| | 5.10.12 | “Two out of three isn't bad”: creating a perfect op-amp | 332 | 5.17.4 | Impedance matching | 382 |
| 5.11 | Auto-zeroing (chopper-stabilized) amplifiers | 333 | | | | |
| | 5.11.1 | Auto-zero op-amp properties | 334 | | | |
| | 5.11.2 | When to use auto-zero op-amps | 338 | | | |

| | | | | | |
|--------------------------------------|---|------------|------------------------------------|--|------------|
| 5.17.5 | Differential amplifier selection criteria | 383 | 7.2.4 | Timing with digital counters | 465 |
| | Review of Chapter 5 | 388 | | Review of Chapter 7 | 470 |
| SIX: Filters | | 391 | EIGHT: Low-Noise Techniques | | 473 |
| 6.1 | Introduction | 391 | 8.1 | “Noise” | 473 |
| 6.2 | Passive filters | 391 | 8.1.1 | Johnson (Nyquist) noise | 474 |
| 6.2.1 | Frequency response with <i>RC</i> filters | 391 | 8.1.2 | Shot noise | 475 |
| 6.2.2 | Ideal performance with <i>LC</i> filters | 393 | 8.1.3 | 1/ <i>f</i> noise (flicker noise) | 476 |
| 6.2.3 | Several simple examples | 393 | 8.1.4 | Burst noise | 477 |
| 6.2.4 | Enter active filters: an overview | 396 | 8.1.5 | Band-limited noise | 477 |
| 6.2.5 | Key filter performance criteria | 399 | 8.1.6 | Interference | 478 |
| 6.2.6 | Filter types | 400 | 8.2 | Signal-to-noise ratio and noise figure | 478 |
| 6.2.7 | Filter implementation | 405 | 8.2.1 | Noise power density and bandwidth | 479 |
| 6.3 | Active-filter circuits | 406 | 8.2.2 | Signal-to-noise ratio | 479 |
| 6.3.1 | VCVS circuits | 407 | 8.2.3 | Noise figure | 479 |
| 6.3.2 | VCVS filter design using our simplified table | 407 | 8.2.4 | Noise temperature | 480 |
| 6.3.3 | State-variable filters | 410 | 8.3 | Bipolar transistor amplifier noise | 481 |
| 6.3.4 | Twin-T notch filters | 414 | 8.3.1 | Voltage noise, e_n | 481 |
| 6.3.5 | Allpass filters | 415 | 8.3.2 | Current noise i_n | 483 |
| 6.3.6 | Switched-capacitor filters | 415 | 8.3.3 | BJT voltage noise, revisited | 484 |
| 6.3.7 | Digital signal processing | 418 | 8.3.4 | A simple design example: loudspeaker as microphone | 486 |
| 6.3.8 | Filter miscellany | 422 | 8.3.5 | Shot noise in current sources and emitter followers | 487 |
| | Additional Exercises for Chapter 6 | 422 | 8.4 | Finding e_n from noise-figure specifications | 489 |
| | Review of Chapter 6 | 423 | 8.4.1 | Step 1: NF versus I_C | 489 |
| SEVEN: Oscillators and Timers | | 425 | 8.4.2 | Step 2: NF versus R_s | 489 |
| 7.1 | Oscillators | 425 | 8.4.3 | Step 3: getting to e_n | 490 |
| 7.1.1 | Introduction to oscillators | 425 | 8.4.4 | Step 4: the spectrum of e_n | 491 |
| 7.1.2 | Relaxation oscillators | 425 | 8.4.5 | The spectrum of i_n | 491 |
| 7.1.3 | The classic oscillator-timer chip: the 555 | 428 | 8.4.6 | When operating current is not your choice | 491 |
| 7.1.4 | Other relaxation-oscillator ICs | 432 | 8.5 | Low-noise design with bipolar transistors | 492 |
| 7.1.5 | Sinewave oscillators | 435 | 8.5.1 | Noise-figure example | 492 |
| 7.1.6 | Quartz-crystal oscillators | 443 | 8.5.2 | Charting amplifier noise with e_n and i_n | 493 |
| 7.1.7 | Higher stability: TCXO, OCXO, and beyond | 450 | 8.5.3 | Noise resistance | 494 |
| 7.1.8 | Frequency synthesis: DDS and PLL | 451 | 8.5.4 | Charting comparative noise | 495 |
| 7.1.9 | Quadrature oscillators | 453 | 8.5.5 | Low-noise design with BJTs: two examples | 495 |
| 7.1.10 | Oscillator “jitter” | 457 | 8.5.6 | Minimizing noise: BJTs, FETs, and transformers | 496 |
| 7.2 | Timers | 457 | 8.5.7 | A design example: 40 μ “lightning detector” preamp | 497 |
| 7.2.1 | Step-triggered pulses | 458 | 8.5.8 | Selecting a low-noise bipolar transistor | 500 |
| 7.2.2 | Monostable multivibrators | 461 | 8.5.9 | An extreme low-noise design challenge | 505 |
| 7.2.3 | A monostable application: limiting pulse width and duty cycle | 465 | | | |

| | | | | | |
|---------|--|-----|--|---|-----|
| 8.6 | Low-noise design with JFETs | 509 | 8.11.13 | Test fixture for compensation and calibration | 554 |
| 8.6.1 | Voltage noise of JFETs | 509 | 8.11.14 | A final remark | 555 |
| 8.6.2 | Current noise of JFETs | 511 | 8.12 | Noise measurements and noise sources | 555 |
| 8.6.3 | Design example: low-noise wideband JFET “hybrid” amplifiers | 512 | 8.12.1 | Measurement without a noise source | 555 |
| 8.6.4 | Designs by the masters: SR560 low-noise preamplifier | 512 | 8.12.2 | An example: transistor-noise test circuit | 556 |
| 8.6.5 | Selecting low-noise JFETs | 515 | 8.12.3 | Measurement with a noise source | 556 |
| 8.7 | Charting the bipolar–FET shootout | 517 | 8.12.4 | Noise and signal sources | 558 |
| 8.7.1 | What about MOSFETs? | 519 | 8.13 | Bandwidth limiting and rms voltage measurement | 561 |
| 8.8 | Noise in differential and feedback amplifiers | 520 | 8.13.1 | Limiting the bandwidth | 561 |
| 8.9 | Noise in operational amplifier circuits | 521 | 8.13.2 | Calculating the integrated noise | 563 |
| 8.9.1 | Guide to Table 8.3: choosing low-noise op-amps | 525 | 8.13.3 | Op-amp “low-frequency noise” with asymmetric filter | 564 |
| 8.9.2 | Power-supply rejection ratio | 533 | 8.13.4 | Finding the $1/f$ corner frequency | 566 |
| 8.9.3 | Wrapup: choosing a low-noise op-amp | 533 | 8.13.5 | Measuring the noise voltage | 567 |
| 8.9.4 | Low-noise instrumentation amplifiers and video amplifiers | 533 | 8.13.6 | Measuring the noise current | 569 |
| 8.9.5 | Low-noise hybrid op-amps | 534 | 8.13.7 | Another way: roll-your-own $fA/\sqrt{\text{Hz}}$ instrument | 571 |
| 8.10 | Signal transformers | 535 | 8.13.8 | Noise potpourri | 574 |
| 8.10.1 | A low-noise wideband amplifier with transformer feedback | 536 | 8.14 | Signal-to-noise improvement by bandwidth narrowing | 574 |
| 8.11 | Noise in transimpedance amplifiers | 537 | 8.14.1 | Lock-in detection | 575 |
| 8.11.1 | Summary of the stability problem | 537 | 8.15 | Power-supply noise | 578 |
| 8.11.2 | Amplifier input noise | 538 | 8.15.1 | Capacitance multiplier | 578 |
| 8.11.3 | The $e_n C$ noise problem | 538 | 8.16 | Interference, shielding, and grounding | 579 |
| 8.11.4 | Noise in the transresistance amplifier | 539 | 8.16.1 | Interfering signals | 579 |
| 8.11.5 | An example: wideband JFET photodiode amplifier | 540 | 8.16.2 | Signal grounds | 582 |
| 8.11.6 | Noise versus gain in the transimpedance amplifier | 540 | 8.16.3 | Grounding between instruments | 583 |
| 8.11.7 | Output bandwidth limiting in the transimpedance amplifier | 542 | Additional Exercises for Chapter 8 | | 588 |
| 8.11.8 | Composite transimpedance amplifiers | 543 | Review of Chapter 8 | | 590 |
| 8.11.9 | Reducing input capacitance: bootstrapping the transimpedance amplifier | 547 | NINE: Voltage Regulation and Power Conversion | | |
| 8.11.10 | Isolating input capacitance: cascoding the transimpedance amplifier | 548 | 9.1 | Tutorial: from zener to series-pass linear regulator | 595 |
| 8.11.11 | Transimpedance amplifiers with capacitive feedback | 552 | 9.1.1 | Adding feedback | 596 |
| 8.11.12 | Scanning tunneling microscope preamplifier | 553 | 9.2 | Basic linear regulator circuits with the classic 723 | 598 |
| | | | 9.2.1 | The 723 regulator | 598 |
| | | | 9.2.2 | In defense of the beleaguered 723 | 600 |
| | | | 9.3 | Fully integrated linear regulators | 600 |
| | | | 9.3.1 | Taxonomy of linear regulator ICs | 601 |
| | | | 9.3.2 | Three-terminal fixed regulators | 601 |

| | | | | | |
|--------|--|-----|--------|---|------------|
| 9.3.3 | Three-terminal adjustable regulators | 602 | 9.7.1 | The ac-to-dc input stage | 660 |
| 9.3.4 | 317-style regulator: application hints | 604 | 9.7.2 | The dc-to-dc converter | 662 |
| 9.3.5 | 317-style regulator: circuit examples | 608 | 9.8 | A real-world switcher example | 665 |
| 9.3.6 | Lower-dropout regulators | 610 | 9.8.1 | Switchers: top-level view | 665 |
| 9.3.7 | True low-dropout regulators | 611 | 9.8.2 | Switchers: basic operation | 665 |
| 9.3.8 | Current-reference 3-terminal regulator | 611 | 9.8.3 | Switchers: looking more closely | 668 |
| 9.3.9 | Dropout voltages compared | 612 | 9.8.4 | The “reference design” | 671 |
| 9.3.10 | Dual-voltage regulator circuit example | 613 | 9.8.5 | Wrapup: general comments on line-powered switching power supplies | 672 |
| 9.3.11 | Linear regulator choices | 613 | 9.8.6 | When to use switchers | 672 |
| 9.3.12 | Linear regulator idiosyncrasies | 613 | 9.9 | Inverters and switching amplifiers | 673 |
| 9.3.13 | Noise and ripple filtering | 619 | 9.10 | Voltage references | 674 |
| 9.3.14 | Current sources | 620 | 9.10.1 | Zener diode | 674 |
| 9.4 | Heat and power design | 623 | 9.10.2 | Bandgap (V_{BE}) reference | 679 |
| 9.4.1 | Power transistors and heatsinking | 624 | 9.10.3 | JFET pinch-off (V_P) reference | 680 |
| 9.4.2 | Safe operating area | 627 | 9.10.4 | Floating-gate reference | 681 |
| 9.5 | From ac line to unregulated supply | 628 | 9.10.5 | Three-terminal precision references | 681 |
| 9.5.1 | ac-line components | 629 | 9.10.6 | Voltage reference noise | 682 |
| 9.5.2 | Transformer | 632 | 9.10.7 | Voltage references: additional Comments | 683 |
| 9.5.3 | dc components | 633 | 9.11 | Commercial power-supply modules | 684 |
| 9.5.4 | Unregulated split supply – on the bench! | 634 | 9.12 | Energy storage: batteries and capacitors | 686 |
| 9.5.5 | Linear versus switcher: ripple and noise | 635 | 9.12.1 | Battery characteristics | 687 |
| 9.6 | Switching regulators and dc–dc converters | 636 | 9.12.2 | Choosing a battery | 688 |
| 9.6.1 | Linear versus switching | 636 | 9.12.3 | Energy storage in capacitors | 688 |
| 9.6.2 | Switching converter topologies | 638 | 9.13 | Additional topics in power regulation | 690 |
| 9.6.3 | Inductorless switching converters | 638 | 9.13.1 | Overvoltage crowbars | 690 |
| 9.6.4 | Converters with inductors: the basic non-isolated topologies | 641 | 9.13.2 | Extending input-voltage range | 693 |
| 9.6.5 | Step-down (buck) converter | 642 | 9.13.3 | Foldback current limiting | 693 |
| 9.6.6 | Step-up (boost) converter | 647 | 9.13.4 | Outboard pass transistor | 695 |
| 9.6.7 | Inverting converter | 648 | 9.13.5 | High-voltage regulators | 695 |
| 9.6.8 | Comments on the non-isolated converters | 649 | | Review of Chapter 9 | 699 |
| 9.6.9 | Voltage mode and current mode | 651 | | TEN: Digital Logic | 703 |
| 9.6.10 | Converters with transformers: the basic designs | 653 | 10.1 | Basic logic concepts | 703 |
| 9.6.11 | The flyback converter | 655 | 10.1.1 | Digital versus analog | 703 |
| 9.6.12 | Forward converters | 656 | 10.1.2 | Logic states | 704 |
| 9.6.13 | Bridge converters | 659 | 10.1.3 | Number codes | 705 |
| 9.7 | Ac-line-powered (“offline”) switching converters | 660 | 10.1.4 | Gates and truth tables | 708 |
| | | | 10.1.5 | Discrete circuits for gates | 711 |
| | | | 10.1.6 | Gate-logic example | 712 |
| | | | 10.1.7 | Assertion-level logic notation | 713 |
| | | | 10.2 | Digital integrated circuits: CMOS and Bipolar (TTL) | 714 |
| | | | 10.2.1 | Catalog of common gates | 715 |
| | | | 10.2.2 | IC gate circuits | 717 |
| | | | 10.2.3 | CMOS and bipolar (“TTL”) characteristics | 718 |

| | | | | | |
|---|---|------------|----------------------------------|---|------------|
| 10.2.4 | Three-state and open-collector devices | 720 | 11.3 | An example: pseudorandom byte generator | 770 |
| 10.3 | Combinational logic | 722 | 11.3.1 | How to make pseudorandom bytes | 771 |
| 10.3.1 | Logic identities | 722 | 11.3.2 | Implementation in standard logic | 772 |
| 10.3.2 | Minimization and Karnaugh maps | 723 | 11.3.3 | Implementation with programmable logic | 772 |
| 10.3.3 | Combinational functions available as ICs | 724 | 11.3.4 | Programmable logic – HDL entry | 775 |
| 10.4 | Sequential logic | 728 | 11.3.5 | Implementation with a microcontroller | 777 |
| 10.4.1 | Devices with memory: flip-flops | 728 | 11.4 | Advice | 782 |
| 10.4.2 | Clocked flip-flops | 730 | 11.4.1 | By <i>Technologies</i> | 782 |
| 10.4.3 | Combining memory and gates: sequential logic | 734 | 11.4.2 | By <i>User Communities</i> | 785 |
| 10.4.4 | Synchronizer | 737 | | Review of Chapter 11 | 787 |
| 10.4.5 | Monostable multivibrator | 739 | | | |
| 10.4.6 | Single-pulse generation with flip-flops and counters | 739 | | | |
| 10.5 | Sequential functions available as integrated circuits | 740 | TWELVE: Logic Interfacing | | 790 |
| 10.5.1 | Latches and registers | 740 | 12.1 | CMOS and TTL logic interfacing | 790 |
| 10.5.2 | Counters | 741 | 12.1.1 | Logic family chronology – a brief history | 790 |
| 10.5.3 | Shift registers | 744 | 12.1.2 | Input and output characteristics | 794 |
| 10.5.4 | Programmable logic devices | 745 | 12.1.3 | Interfacing between logic families | 798 |
| 10.5.5 | Miscellaneous sequential functions | 746 | 12.1.4 | Driving digital logic inputs | 802 |
| 10.6 | Some typical digital circuits | 748 | 12.1.5 | Input protection | 804 |
| 10.6.1 | Modulo- n counter: a timing example | 748 | 12.1.6 | Some comments about logic inputs | 805 |
| 10.6.2 | Multiplexed LED digital display | 751 | 12.1.7 | Driving digital logic from comparators or op-amps | 806 |
| 10.6.3 | An n -pulse generator | 752 | 12.2 | An aside: probing digital signals | 808 |
| 10.7 | Micropower digital design | 753 | 12.3 | Comparators | 809 |
| 10.7.1 | Keeping CMOS low power | 754 | 12.3.1 | Outputs | 810 |
| 10.8 | Logic pathology | 755 | 12.3.2 | Inputs | 812 |
| 10.8.1 | dc problems | 755 | 12.3.3 | Other parameters | 815 |
| 10.8.2 | Switching problems | 756 | 12.3.4 | Other cautions | 816 |
| 10.8.3 | Congenital weaknesses of TTL and CMOS | 758 | 12.4 | Driving external digital loads from logic levels | 817 |
| | Additional Exercises for Chapter 10 | 760 | 12.4.1 | Positive loads: direct drive | 817 |
| | Review of Chapter 10 | 762 | 12.4.2 | Positive loads: transistor assisted | 820 |
| ELEVEN: Programmable Logic Devices | | 764 | 12.4.3 | Negative or ac loads | 821 |
| 11.1 | A brief history | 764 | 12.4.4 | Protecting power switches | 823 |
| 11.2 | The hardware | 765 | 12.4.5 | nMOS LSI interfacing | 826 |
| 11.2.1 | The basic PAL | 765 | 12.5 | Optoelectronics: emitters | 829 |
| 11.2.2 | The PLA | 768 | 12.5.1 | Indicators and LEDs | 829 |
| 11.2.3 | The FPGA | 768 | 12.5.2 | Laser diodes | 834 |
| 11.2.4 | The configuration memory | 769 | 12.5.3 | Displays | 836 |
| 11.2.5 | Other programmable logic devices | 769 | 12.6 | Optoelectronics: detectors | 840 |
| 11.2.6 | The software | 769 | | | |

| | | | | | |
|--|---|------------|---------|---|-----|
| 12.6.1 | Photodiodes and phototransistors | 841 | 13.2.8 | PWM as digital-to-analog converter | 888 |
| 12.6.2 | Photomultipliers | 842 | 13.2.9 | Frequency-to-voltage converters | 890 |
| 12.7 | Optocouplers and relays | 843 | 13.2.10 | Rate multiplier | 890 |
| 12.7.1 | I: Phototransistor output optocouplers | 844 | 13.2.11 | Choosing a DAC | 891 |
| 12.7.2 | II: Logic-output optocouplers | 844 | 13.3 | Some DAC application examples | 891 |
| 12.7.3 | III: Gate driver optocouplers | 846 | 13.3.1 | General-purpose laboratory source | 891 |
| 12.7.4 | IV: Analog-oriented optocouplers | 847 | 13.3.2 | Eight-channel source | 893 |
| 12.7.5 | V: Solid-state relays (transistor output) | 848 | 13.3.3 | Nanoamp wide-compliance bipolarity current source | 894 |
| 12.7.6 | VI: Solid-state relays (triac/SCR output) | 849 | 13.3.4 | Precision coil driver | 897 |
| 12.7.7 | VII: ac-input optocouplers | 851 | 13.4 | Converter linearity – a closer look | 899 |
| 12.7.8 | Interruptions | 851 | 13.5 | Analog-to-digital converters | 900 |
| 12.8 | Optoelectronics: fiber-optic digital links | 852 | 13.5.1 | Digitizing: aliasing, sampling rate, and sampling depth | 900 |
| 12.8.1 | TOSLINK | 852 | 13.5.2 | ADC Technologies | 902 |
| 12.8.2 | Versatile Link | 854 | 13.6 | ADCs I: Parallel (“flash”) encoder | 903 |
| 12.8.3 | ST/SC glass-fiber modules | 855 | 13.6.1 | Modified flash encoders | 903 |
| 12.8.4 | Fully integrated high-speed fiber-transceiver modules | 855 | 13.6.2 | Driving flash, folding, and RF ADCs | 904 |
| 12.9 | Digital signals and long wires | 856 | 13.6.3 | Undersampling flash-converter example | 907 |
| 12.9.1 | On-board interconnections | 856 | 13.7 | ADCs II: Successive approximation | 908 |
| 12.9.2 | Intercard connections | 858 | 13.7.1 | A simple SAR example | 909 |
| 12.10 | Driving Cables | 858 | 13.7.2 | Variations on successive approximation | 909 |
| 12.10.1 | Coaxial cable | 858 | 13.7.3 | An A/D conversion example | 910 |
| 12.10.2 | The right way – I: Far-end termination | 860 | 13.8 | ADCs III: integrating | 912 |
| 12.10.3 | Differential-pair cable | 864 | 13.8.1 | Voltage-to-frequency conversion | 912 |
| 12.10.4 | RS-232 | 871 | 13.8.2 | Single-slope integration | 914 |
| 12.10.5 | Wrapup | 874 | 13.8.3 | Integrating converters | 914 |
| Review of Chapter 12 | | 875 | 13.8.4 | Dual-slope integration | 914 |
| | | | 13.8.5 | Analog switches in conversion applications (a detour) | 916 |
| THIRTEEN : Digital meets Analog | | 879 | 13.8.6 | Designs by the masters: Agilent’s world-class “multislope” converters | 918 |
| 13.1 | Some preliminaries | 879 | 13.9 | ADCs IV: delta-sigma | 922 |
| 13.1.1 | The basic performance parameters | 879 | 13.9.1 | A simple delta-sigma for our suntan monitor | 922 |
| 13.1.2 | Codes | 880 | 13.9.2 | Demystifying the delta-sigma converter | 923 |
| 13.1.3 | Converter errors | 880 | 13.9.3 | $\Delta\Sigma$ ADC and DAC | 923 |
| 13.1.4 | Stand-alone versus integrated | 880 | 13.9.4 | The $\Delta\Sigma$ process | 924 |
| 13.2 | Digital-to-analog converters | 881 | 13.9.5 | An aside: “noise shaping” | 927 |
| 13.2.1 | Resistor-string DACs | 881 | 13.9.6 | The bottom line | 928 |
| 13.2.2 | $R-2R$ ladder DACs | 882 | 13.9.7 | A simulation | 928 |
| 13.2.3 | Current-steering DACs | 883 | 13.9.8 | What about DACs? | 930 |
| 13.2.4 | Multiplying DACs | 884 | | | |
| 13.2.5 | Generating a voltage output | 885 | | | |
| 13.2.6 | Six DACs | 886 | | | |
| 13.2.7 | Delta-sigma DACs | 888 | | | |

| | | | | | |
|---------|--|-----|--|--|------|
| 13.9.9 | Pros and Cons of $\Delta\Sigma$ oversampling converters | 931 | 13.14.8 | A “hybrid digital filter” | 983 |
| 13.9.10 | Idle tones | 932 | | Additional Exercises for Chapter 13 | 984 |
| 13.9.11 | Some delta-sigma application examples | 932 | | Review of Chapter 13 | 985 |
| 13.10 | ADCs: choices and tradeoffs | 938 | FOURTEEN: Computers, Controllers, and Data Links 989 | | |
| 13.10.1 | Delta-sigma and the competition | 938 | 14.1 | Computer architecture: CPU and data bus | 990 |
| 13.10.2 | Sampling versus averaging ADCs: noise | 940 | 14.1.1 | CPU | 990 |
| 13.10.3 | Micropower A/D converters | 941 | 14.1.2 | Memory | 991 |
| 13.11 | Some unusual A/D and D/A converters | 942 | 14.1.3 | Mass memory | 991 |
| 13.11.1 | ADE7753 multifunction ac power metering IC | 943 | 14.1.4 | Graphics, network, parallel, and serial ports | 992 |
| 13.11.2 | AD7873 touchscreen digitizer | 944 | 14.1.5 | Real-time I/O | 992 |
| 13.11.3 | AD7927 ADC with sequencer | 945 | 14.1.6 | Data bus | 992 |
| 13.11.4 | AD7730 precision bridge-measurement subsystem | 945 | 14.2 | A computer instruction set | 993 |
| 13.12 | Some A/D conversion system examples | 946 | 14.2.1 | Assembly language and machine language | 993 |
| 13.12.1 | Multiplexed 16-channel data-acquisition system | 946 | 14.2.2 | Simplified “x86” instruction set | 993 |
| 13.12.2 | Parallel multichannel successive-approximation data-acquisition system | 950 | 14.2.3 | A programming example | 996 |
| 13.12.3 | Parallel multichannel delta-sigma data-acquisition system | 952 | 14.3 | Bus signals and interfacing | 997 |
| 13.13 | Phase-locked loops | 955 | 14.3.1 | Fundamental bus signals: data, address, strobe | 997 |
| 13.13.1 | Introduction to phase-locked loops | 955 | 14.3.2 | Programmed I/O: data out | 998 |
| 13.13.2 | PLL components | 957 | 14.3.3 | Programming the XY vector display | 1000 |
| 13.13.3 | PLL design | 960 | 14.3.4 | Programmed I/O: data in | 1001 |
| 13.13.4 | Design example: frequency multiplier | 961 | 14.3.5 | Programmed I/O: status registers | 1002 |
| 13.13.5 | PLL capture and lock | 964 | 14.3.6 | Programmed I/O: command registers | 1004 |
| 13.13.6 | Some PLL applications | 966 | 14.3.7 | Interrupts | 1005 |
| 13.13.7 | Wrapup: noise and jitter rejection in PLLs | 974 | 14.3.8 | Interrupt handling | 1006 |
| 13.14 | Pseudorandom bit sequences and noise generation | 974 | 14.3.9 | Interrupts in general | 1008 |
| 13.14.1 | Digital-noise generation | 974 | 14.3.10 | Direct memory access | 1010 |
| 13.14.2 | Feedback shift register sequences | 975 | 14.3.11 | Summary of PC104/ISA 8-bit bus signals | 1012 |
| 13.14.3 | Analog noise generation from maximal-length sequences | 977 | 14.3.12 | The PC104 as an embedded single-board computer | 1013 |
| 13.14.4 | Power spectrum of shift-register sequences | 977 | 14.4 | Memory types | 1014 |
| 13.14.5 | Low-pass filtering | 979 | 14.4.1 | Volatile and non-volatile memory | 1014 |
| 13.14.6 | Wrapup | 981 | 14.4.2 | Static versus dynamic RAM | 1015 |
| 13.14.7 | “True” random noise generators | 982 | 14.4.3 | Static RAM | 1016 |
| | | | 14.4.4 | Dynamic RAM | 1018 |
| | | | 14.4.5 | Nonvolatile memory | 1021 |
| | | | 14.4.6 | Memory wrapup | 1026 |
| | | | 14.5 | Other buses and data links: overview | 1027 |
| | | | 14.6 | Parallel buses and data links | 1028 |
| | | | 14.6.1 | Parallel chip “bus” interface – an example | 1028 |

| | | | | | |
|----------------------------------|--|-------------|---|--|------|
| 14.6.2 | Parallel chip data links – two high-speed examples | 1030 | 15.7 | Design example 5: stabilized mechanical platform | 1077 |
| 14.6.3 | Other parallel computer buses | 1030 | 15.8 | Peripheral ICs for microcontrollers | 1078 |
| 14.6.4 | Parallel peripheral buses and data links | 1031 | 15.8.1 | Peripherals with direct connection | 1079 |
| 14.7 | Serial buses and data links | 1032 | 15.8.2 | Peripherals with SPI connection | 1082 |
| 14.7.1 | SPI | 1032 | 15.8.3 | Peripherals with I ² C connection | 1084 |
| 14.7.2 | I ² C 2-wire interface (“TWI”) | 1034 | 15.8.4 | Some important hardware constraints | 1086 |
| 14.7.3 | Dallas–Maxim “1-wire” serial interface | 1035 | 15.9 | Development environment | 1086 |
| 14.7.4 | JTAG | 1036 | 15.9.1 | Software | 1086 |
| 14.7.5 | Clock-be-gone: clock recovery | 1037 | 15.9.2 | Real-time programming constraints | 1088 |
| 14.7.6 | SATA, eSATA, and SAS | 1037 | 15.9.3 | Hardware | 1089 |
| 14.7.7 | PCI Express | 1037 | 15.9.4 | The Arduino Project | 1092 |
| 14.7.8 | Asynchronous serial (RS-232, RS-485) | 1038 | 15.10 | Wrapup | 1092 |
| 14.7.9 | Manchester coding | 1039 | 15.10.1 | How expensive are the tools? | 1092 |
| 14.7.10 | Biphase coding | 1041 | 15.10.2 | When to use microcontrollers | 1093 |
| 14.7.11 | RLL binary: bit stuffing | 1041 | 15.10.3 | How to select a microcontroller | 1094 |
| 14.7.12 | RLL coding: 8b/10b and others | 1041 | 15.10.4 | A parting shot | 1094 |
| 14.7.13 | USB | 1042 | Review of Chapter 15 | 1095 | |
| 14.7.14 | FireWire | 1042 | APPENDIX A: Math Review | 1097 | |
| 14.7.15 | Controller Area Network (CAN) | 1043 | A.1 | Trigonometry, exponentials, and logarithms | 1097 |
| 14.7.16 | Ethernet | 1045 | A.2 | Complex numbers | 1097 |
| 14.8 | Number formats | 1046 | A.3 | Differentiation (Calculus) | 1099 |
| 14.8.1 | Integers | 1046 | A.3.1 | Derivatives of some common functions | 1099 |
| 14.8.2 | Floating-point numbers | 1047 | A.3.2 | Some rules for combining derivatives | 1100 |
| Review of Chapter 14 | | 1049 | A.3.3 | Some examples of differentiation | 1100 |
| FIFTEEN: Microcontrollers | | 1053 | APPENDIX B: How to Draw Schematic Diagrams | 1101 | |
| 15.1 | Introduction | 1053 | B.1 | General principles | 1101 |
| 15.2 | Design example 1: suntan monitor (V) | 1054 | B.2 | Rules | 1101 |
| 15.2.1 | Implementation with a microcontroller | 1054 | B.3 | Hints | 1103 |
| 15.2.2 | Microcontroller code (“firmware”) | 1056 | B.4 | A humble example | 1103 |
| 15.3 | Overview of popular microcontroller families | 1059 | APPENDIX C: Resistor Types | 1104 | |
| 15.3.1 | On-chip peripherals | 1061 | C.1 | Some history | 1104 |
| 15.4 | Design example 2: ac power control | 1062 | C.2 | Available resistance values | 1104 |
| 15.4.1 | Microcontroller implementation | 1062 | C.3 | Resistance marking | 1105 |
| 15.4.2 | Microcontroller code | 1064 | C.4 | Resistor types | 1105 |
| 15.5 | Design example 3: frequency synthesizer | 1065 | C.5 | Confusion derby | 1105 |
| 15.5.1 | Microcontroller code | 1067 | APPENDIX D: Thévenin’s Theorem | 1107 | |
| 15.6 | Design example 4: thermal controller | 1069 | D.1 | The proof | 1107 |
| 15.6.1 | The hardware | 1070 | | | |
| 15.6.2 | The control loop | 1074 | | | |
| 15.6.3 | Microcontroller code | 1075 | | | |

| | | | | | |
|--|---|-------------|---|--|-------------|
| D.1.1 | Two examples – voltage dividers | 1107 | I.3 | Recording analog-format broadcast or cable television | 1135 |
| D.2 | Norton's theorem | 1108 | I.4 | Digital television: what is it? | 1136 |
| D.3 | Another example | 1108 | I.5 | Digital television: broadcast and cable delivery | 1138 |
| D.4 | Millman's theorem | 1108 | I.6 | Direct satellite television | 1139 |
| APPENDIX E: LC Butterworth Filters | | 1109 | I.7 | Digital video streaming over internet | 1140 |
| E.1 | Lowpass filter | 1109 | I.8 | Digital cable: premium services and conditional access | 1141 |
| E.2 | Highpass filter | 1109 | I.8.1 | Digital cable: video-on-demand | 1141 |
| E.3 | Filter examples | 1109 | I.8.2 | Digital cable: switched broadcast | 1142 |
| APPENDIX F: Load Lines | | 1112 | I.9 | Recording digital television | 1142 |
| F.1 | An example | 1112 | I.10 | Display technology | 1142 |
| F.2 | Three-terminal devices | 1112 | I.11 | Video connections: analog and digital | 1143 |
| F.3 | Nonlinear devices | 1113 | APPENDIX J: SPICE Primer | | 1146 |
| APPENDIX G: The Curve Tracer | | 1115 | J.1 | Setting up ICAP SPICE | 1146 |
| APPENDIX H: Transmission Lines and Impedance Matching | | 1116 | J.2 | Entering a Diagram | 1146 |
| H.1 | Some properties of transmission lines | 1116 | J.3 | Running a simulation | 1146 |
| H.1.1 | Characteristic impedance | 1116 | J.3.1 | Schematic entry | 1146 |
| H.1.2 | Termination: pulses | 1117 | J.3.2 | Simulation: frequency sweep | 1147 |
| H.1.3 | Termination: sinusoidal signals | 1120 | J.3.3 | Simulation: input and output waveforms | 1147 |
| H.1.4 | Loss in transmission lines | 1121 | J.4 | Some final points | 1148 |
| H.2 | Impedance matching | 1122 | J.5 | A detailed example: exploring amplifier distortion | 1148 |
| H.2.1 | Resistive (lossy) broadband matching network | 1123 | J.6 | Expanding the parts database | 1149 |
| H.2.2 | Resistive attenuator | 1123 | APPENDIX K: "Where Do I Go to Buy Electronic Goodies?" | | 1150 |
| H.2.3 | Transformer (lossless) broadband matching network | 1124 | APPENDIX L: Workbench Instruments and Tools | | 1152 |
| H.2.4 | Reactive (lossless) narrowband matching networks | 1125 | APPENDIX M: Catalogs, Magazines, Databases | | 1153 |
| H.3 | Lumped-element delay lines and pulse-forming networks | 1126 | APPENDIX N: Further Reading and References | | 1154 |
| H.4 | Epilogue: ladder derivation of characteristic impedance | 1127 | APPENDIX O: The Oscilloscope | | 1158 |
| H.4.1 | First method: terminated line | 1127 | O.1 | The analog oscilloscope | 1158 |
| H.4.2 | Second method: semi-infinite line | 1127 | O.1.1 | Vertical | 1158 |
| H.4.3 | Postscript: lumped-element delay lines | 1128 | O.1.2 | Horizontal | 1158 |
| APPENDIX I: Television: A Compact Tutorial | | 1131 | O.1.3 | Triggering | 1159 |
| I.1 | Television: video plus audio | 1131 | O.1.4 | Hints for beginners | 1160 |
| I.1.1 | The audio | 1131 | O.1.5 | Probes | 1160 |
| I.1.2 | The video | 1132 | O.1.6 | Grounds | 1161 |
| I.2 | Combining and sending the audio + video: modulation | 1133 | O.1.7 | Other analog scope features | 1161 |
| | | | O.2 | The digital oscilloscope | 1162 |

| | | | | |
|-------|-------------------|------|---|-------------|
| O.2.1 | What's different? | 1162 | APPENDIX P: Acronyms and Abbreviations | 1166 |
| O.2.2 | Some cautions | 1164 | Index | 1171 |