

CONTENTS

List of Tables

Preface to the Third Edition

Preface to the Second Edition

Preface to the First Edition

ONE: Foundations

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	2
1.2.3	Voltage dividers	3
1.2.4	Voltage sources and current sources	4
1.2.5	Thévenin equivalent circuit	5
1.2.6	Small-signal resistance	6
1.2.7	An example: “It’s too hot!”	7
1.3	Signals	8
1.3.1	Sinusoidal signals	9
1.3.2	Signal amplitudes and decibels	10
1.3.3	Other signals	11
1.3.4	Logic levels	12
1.3.5	Signal sources	13
1.4	Capacitors and ac circuits	14
1.4.1	Capacitors	15
1.4.2	RC circuits: V and I versus time	16
1.4.3	Differentiators	17
1.4.4	Integrators	18
1.4.5	Not quite perfect...	19
1.5	Inductors and transformers	20
1.5.1	Inductors	21
1.5.2	Transformers	22
1.6	Diodes and diode circuits	23
1.6.1	Diodes	24
1.6.2	Rectification	25
1.6.3	Power-supply filtering	26
1.6.4	Rectifier configurations for power supplies	27

xxii	1.6.5	Regulators	28
xxv	1.6.6	Circuit applications of diodes	29
xxviii	1.6.7	Inductive loads and diode protection	30
xxx	1.6.8	Interlude: inductors as friends	31
1	1.7	Impedance and reactance	32
1	1.7.1	Frequency analysis of reactive circuits	33
1	1.7.2	Reactance of inductors	34
1	1.7.3	Voltages and currents as complex numbers	35
1	1.7.4	Reactance of capacitors and inductors	36
1	1.7.5	Ohm’s law generalized	37
1	1.7.6	Power in reactive circuits	38
1	1.7.7	Voltage dividers generalized	39
1	1.7.8	RC highpass filters	40
1	1.7.9	RC lowpass filters	41
1	1.7.10	RC differentiators and integrators in the frequency domain	42
1	1.7.11	Inductors versus capacitors	43
1	1.7.12	Phasor diagrams	44
1	1.7.13	“Poles” and decibels per octave	45
1	1.7.14	Resonant circuits	46
1	1.7.15	LC filters	47
1	1.7.16	Other capacitor applications	48
1	1.7.17	Thévenin’s theorem generalized	49
1	1.8	Putting it all together – an AM radio	50
1	1.9	Other passive components	51
1	1.9.1	Electromechanical devices: switches	52
1	1.9.2	Electromechanical devices: relays	53
1	1.9.3	Connectors	54
1	1.9.4	Indicators	55
1	1.9.5	Variable components	56
1	1.10	A parting shot: confusing markings and itty-bitty components	57
1	1.10.1	Surface-mount technology: the joy and the pain	58

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

3.5.3	Power switching from logic levels	382	4.4.4	Bandwidth and the op-amp current source	254
3.5.4	Power switching cautions	192	4.5	A detailed look at selected op-amp circuits	254
3.5.5	MOSFETs versus BJTs as high-current switches	196	4.5.1	Active peak detector	254
3.5.6	Some power MOSFET circuit examples	201	4.5.2	Sample-and-hold	256
3.5.7	IGBTs and other power semiconductors	202	4.5.3	Active clamp	257
3.6	MOSFETs in linear applications	207	4.5.4	Absolute-value circuit	257
3.6.1	High-voltage piezo amplifier	208	4.5.5	A closer look at the integrator	257
3.6.2	Some depletion-mode circuits	208	4.5.6	A circuit cure for FET leakage	259
3.6.3	Paralleling MOSFETs	209	4.5.7	Differentiators	260
3.6.4	Thermal runaway	212	4.6	Op-amp operation with a single power supply	261
	Review of Chapter 3	214	4.6.1	Biassing single-supply ac amplifiers	261
	Supplement: MOSFET gate drivers	219	4.6.2	Capacitive loads	264
		222	4.6.3	"Single-supply" op-amps	265
		223	4.6.4	Example: voltage-controlled oscillator	267
		223	4.6.5	VCO implementation: through-hole versus surface-mount	268
4.1	Introduction to op-amps – the "perfect component"	223	4.6.6	Zero-crossing detector	269
4.1.1	Feedback and op-amps	223	4.6.7	An op-amp table	270
4.1.2	Operational amplifiers	224	4.7	Other amplifiers and op-amp types	270
4.1.3	The golden rules	225	4.8	Some typical op-amp circuits	274
4.2	Basic op-amp circuits	225	4.8.1	General-purpose lab amplifier	274
4.2.1	Inverting amplifier	225	4.8.2	Stuck-node tracer	276
4.2.2	Noninverting amplifier	226	4.8.3	Load-current-sensing circuit	277
4.2.3	Follower	227	4.8.4	Integrating suntan monitor	278
4.2.4	Difference amplifier	227	4.9	Feedback amplifier frequency compensation	280
4.2.5	Current sources	228	4.9.1	Gain and phase shift versus frequency	281
4.2.6	Integrators	230	4.9.2	Amplifier compensation methods	282
4.2.7	Basic cautions for op-amp circuits	231	4.9.3	Frequency response of the feedback network	284
4.3	An op-amp smorgasbord	232		Additional Exercises for Chapter 4	287
4.3.1	Linear circuits	232		Review of Chapter 4	288
4.3.2	Nonlinear circuits	236			
4.3.3	Op-amp application: triangle-wave oscillator	239	FIVE: Precision Circuits		292
4.3.4	Op-amp application: pinch-off voltage tester	239	5.1	Precision op-amp design techniques	292
4.3.5	Programmable pulse-width generator	241	5.1.1	Precision versus dynamic range	292
4.3.6	Active lowpass filter	241	5.1.2	Error budget	293
4.4	A detailed look at op-amp behavior	242	5.2	An example: the millivoltmeter, revisited	293
4.4.1	Departure from ideal op-amp performance	243	5.2.1	The challenge: 10 mV, 1%, 10 MΩ, 1.8 V single supply	293
4.4.2	Effects of op-amp limitations on circuit behavior	249	5.2.2	The solution: precision RRIO current source	294
4.4.3	Example: sensitive millivoltmeter	253			

5.3	The lessons: error budget, unspecified parameters	295	5.11.1	Auto-zero op-amp properties	334
5.4	Another example: precision amplifier with null offset	297	5.11.2	When to use auto-zero op-amps	338
	5.4.1 Circuit description	297	5.11.3	Selecting an auto-zero op-amp	338
5.5	A precision-design error budget	298	5.11.4	Auto-zero miscellany	340
5.6	Component errors	299	5.12	Designs by the masters: Agilent's accurate DMMs	342
	5.6.1 Gain-setting resistors	300	5.12.1	<i>It's impossible!</i>	342
	5.6.2 The holding capacitor	300	5.12.2	Wrong – it <i>is</i> possible!	342
	5.6.3 Nulling switch	300	5.12.3	Block diagram: a simple plan	343
5.7	Amplifier input errors	301	5.12.4	The 34401A 6.5-digit front end	343
	5.7.1 Input impedance	302	5.12.5	The 34420A 7.5-digit frontend	344
	5.7.2 Input bias current	302	5.13	Difference, differential, and instrumentation amplifiers: introduction	347
	5.7.3 Voltage offset	304	5.14	Difference amplifier	348
	5.7.4 Common-mode rejection	305	5.14.1	Basic circuit operation	348
	5.7.5 Power-supply rejection	306	5.14.2	Some applications	349
	5.7.6 Nulling amplifier: input errors	306	5.14.3	Performance parameters	352
5.8	Amplifier output errors	307	5.14.4	Circuit variations	355
	5.8.1 Slew rate: general considerations	307	5.15	Instrumentation amplifier	356
	5.8.2 Bandwidth and settling time	308	5.15.1	A first (but naive) guess	357
	5.8.3 Crossover distortion and output impedance	309	5.15.2	Classic three-op-amp instrumentation amplifier	357
	5.8.4 Unity-gain power buffers	311	5.15.3	Input-stage considerations	358
	5.8.5 Gain error	312	5.15.4	A “roll-your-own” instrumentation amplifier	359
	5.8.6 Gain nonlinearity	312	5.15.5	A riff on robust input protection	362
	5.8.7 Phase error and “active compensation”	314	5.16	Instrumentation amplifier miscellany	362
5.9	RRIO op-amps: the good, the bad, and the ugly	315	5.16.1	Input current and noise	362
	5.9.1 Input issues	316	5.16.2	Common-mode rejection	364
	5.9.2 Output issues	316	5.16.3	Source impedance and CMRR	365
5.10	Choosing a precision op-amp	319	5.16.4	EMI and input protection	365
	5.10.1 “Seven precision op-amps”	319	5.16.5	Offset and CMRR trimming	366
	5.10.2 Number per package	322	5.16.6	Sensing at the load	366
	5.10.3 Supply voltage, signal range	322	5.16.7	Input bias path	366
	5.10.4 Single-supply operation	322	5.16.8	Output voltage range	366
	5.10.5 Offset voltage	323	5.16.9	Application example: current source	367
	5.10.6 Voltage noise	323	5.16.10	Other configurations	368
	5.10.7 Bias current	325	5.16.11	Chopper and auto-zero instrumentation amplifiers	370
	5.10.8 Current noise	326	5.16.12	Programmable gain instrumentation amplifiers	370
	5.10.9 CMRR and PSRR	328	5.16.13	Generating a differential output	372
	5.10.10 GBW, f_T , slew rate and “ m ,” and settling time	328	5.17	Fully differential amplifiers	373
	5.10.11 Distortion	329	5.17.1	Differential amplifiers: basic concepts	374
	5.10.12 “Two out of three isn't bad”: creating a perfect op-amp	332	5.17.2	Differential amplifier application example: wideband analog link	380
5.11	Auto-zeroing (chopper-stabilized) amplifiers	333	5.17.3	Differential-input ADCs	380

5.17.4 Impedance matching	382	9.7	limiting pulse width and duty cycle	465
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				
6.1 Introduction	391	EIGHT: Low-Noise Techniques		
6.2 Passive filters	391	8.1	"Noise"	473
6.2.1 Frequency response with <i>RC</i> filters	391	8.1.1	Johnson (Nyquist) noise	474
6.2.2 Ideal performance with <i>LC</i> filters	393	8.1.2	Shot noise	475
6.2.3 Several simple examples	393	8.1.3	<i>1/f</i> noise (flicker noise)	476
6.2.4 Enter active filters: an overview	396	8.1.4	Burst noise	477
6.2.5 Key filter performance criteria	399	8.1.5	Band-limited noise	477
6.2.6 Filter types	400	8.1.6	Interference	478
6.2.7 Filter implementation	405	8.2	Signal-to-noise ratio and noise figure	478
6.3 Active-filter circuits	406	8.2.1	Noise power density and bandwidth	479
6.3.1 VCVS circuits	407	8.2.2	Signal-to-noise ratio	479
6.3.2 VCVS filter design using our simplified table	407	8.2.3	Noise figure	479
6.3.3 State-variable filters	410	8.2.4	Noise temperature	480
6.3.4 Twin-T notch filters	414	8.3	Bipolar transistor amplifier noise	481
6.3.5 Allpass filters	415	8.3.1	Voltage noise, e_n	481
6.3.6 Switched-capacitor filters	415	8.3.2	Current noise i_n	483
6.3.7 Digital signal processing	418	8.3.3	BJT voltage noise, revisited	484
6.3.8 Filter miscellany	422	8.3.4	A simple design example: loudspeaker as microphone	486
Additional Exercises for Chapter 6	422	8.3.5	Shot noise in current sources and emitter followers	487
Review of Chapter 6	423	8.4	Finding e_n from noise-figure specifications	489
SEVEN: Oscillators and Timers				
7.1 Oscillators	425	8.4.1	Step 1: NF versus I_C	489
7.1.1 Introduction to oscillators	425	8.4.2	Step 2: NF versus R_s	489
7.1.2 Relaxation oscillators	425	8.4.3	Step 3: getting to e_n	490
7.1.3 The classic oscillator-timer chip: the 555	428	8.4.4	Step 4: the spectrum of e_n	491
7.1.4 Other relaxation-oscillator ICs	432	8.4.5	The spectrum of i_n	491
7.1.5 Sinewave oscillators	435	8.4.6	When operating current is not your choice	491
7.1.6 Quartz-crystal oscillators	443	8.5	Low-noise design with bipolar transistors	492
7.1.7 Higher stability: TCXO, OCXO, and beyond	450	8.5.1	Noise-figure example	492
7.1.8 Frequency synthesis: DDS and PLL	451	8.5.2	Charting amplifier noise with e_n and i_n	493
7.1.9 Quadrature oscillators	453	8.5.3	Noise resistance	494
7.1.10 Oscillator "jitter"	457	8.5.4	Charting comparative noise	495
7.2 Timers	457	8.5.5	Low-noise design with BJTs: two examples	495
7.2.1 Step-triggered pulses	458	8.5.6	Minimizing noise: BJTs, FETs, and transformers	496
7.2.2 Monostable multivibrators	461	8.5.7	A design example: 40¢ "lightning detector" preamp	497
7.2.3 A monostable application:	469	8.5.8	Selecting a low-noise bipolar transistor	498
				500

8.5.9	An extreme low-noise design challenge	505	8.11.12	Scanning tunneling microscope preamplifier	553
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
			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	9.7	Ac-line-powered (“offline”) switching converters	888
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	660
9.3.5	317-style regulator: circuit examples	608	9.8	A real-world switcher example	662
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	893
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
			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)	924
			10.2.1	Catalog of common gates	714
			10.2.2	IC gate circuits	715
					717

10.2.3	CMOS and bipolar ("TTL") characteristics	718	11.2.5	Other programmable logic devices	769
10.2.4	Three-state and open-collector devices	720	11.2.6	The software	769
10.3	Combinational logic	722	11.3	An example: pseudorandom byte generator	770
10.3.1	Logic identities	722	11.3.1	How to make pseudorandom bytes	771
10.3.2	Minimization and Karnaugh maps	723	11.3.2	Implementation in standard logic	772
10.3.3	Combinational functions available as ICs	724	11.3.3	Implementation with programmable logic	772
10.4	Sequential logic	728	11.3.4	Programmable logic – HDL entry	775
10.4.1	Devices with memory: flip-flops	728	11.3.5	Implementation with a microcontroller	777
10.4.2	Clocked flip-flops	730	11.4	Advice	782
10.4.3	Combining memory and gates: sequential logic	734	11.4.1	By Technologies	782
10.4.4	Synchronizer	737	11.4.2	By User Communities	785
10.4.5	Monostable multivibrator	739		Review of Chapter 11	787
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	13.2.7 Delta-sigma DACs	888
12.6 Optoelectronics: detectors	840	13.2.8 PWM as digital-to-analog converter	888
12.6.1 Photodiodes and phototransistors	841	13.2.9 Frequency-to-voltage converters	890
12.6.2 Photomultipliers	842	13.2.10 Rate multiplier	890
12.7 Optocouplers and relays	843	13.2.11 Choosing a DAC	891
12.7.1 I: Phototransistor output optocouplers	844	13.3 Some DAC application examples	891
12.7.2 II: Logic-output optocouplers	844	13.3.1 General-purpose laboratory source	891
12.7.3 III: Gate driver optocouplers	846	13.3.2 Eight-channel source	893
12.7.4 IV: Analog-oriented optocouplers	847	13.3.3 Nanoamp wide-compliance bipolarity current source	894
12.7.5 V: Solid-state relays (transistor output)	848	13.3.4 Precision coil driver	897
12.7.6 VI: Solid-state relays (triac/SCR output)	849	13.4 Converter linearity – a closer look	899
12.7.7 VII: ac-input optocouplers	851	13.5 Analog-to-digital converters	900
12.7.8 Interrupters	851	13.5.1 Digitizing: aliasing, sampling rate, and sampling depth	900
12.8 Optoelectronics: fiber-optic digital links	852	13.5.2 ADC Technologies	902
12.8.1 TOSLINK	852	13.6 ADCs I: Parallel (“flash”) encoder	903
12.8.2 Versatile Link	854	13.6.1 Modified flash encoders	903
12.8.3 ST/SC glass-fiber modules	855	13.6.2 Driving flash, folding, and RF ADCs	904
12.8.4 Fully integrated high-speed fiber-transceiver modules	855	13.6.3 Undersampling flash-converter example	907
12.9 Digital signals and long wires	856	13.7 ADCs II: Successive approximation	908
12.9.1 On-board interconnections	856	13.7.1 A simple SAR example	909
12.9.2 Intercard connections	858	13.7.2 Variations on successive approximation	909
12.10 Driving Cables	858	13.7.3 An A/D conversion example	910
12.10.1 Coaxial cable	858	13.8 ADCs III: integrating	912
12.10.2 The right way – I: Far-end termination	860	13.8.1 Voltage-to-frequency conversion	912
12.10.3 Differential-pair cable	864	13.8.2 Single-slope integration	914
12.10.4 RS-232	871	13.8.3 Integrating converters	914
12.10.5 Wrapup	874	13.8.4 Dual-slope integration	914
Review of Chapter 12	875	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		
13.2.4 Multiplying DACs	884		
13.2.5 Generating a voltage output	885		
13.2.6 Six DACs	886		

13.9.8 What about DACs?	930	13.14.7 "True" random noise generators	982
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
		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	15.6.3	Microcontroller code	1075
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			
15.1	Introduction	1053		APPENDIX B: How to Draw Schematic Diagrams	1101
15.2	Design example 1: suntan monitor (V)	1054	B.1	General principles	1101
15.2.1	Implementation with a microcontroller	1054	B.2	Rules	1101
15.2.2	Microcontroller code (“firmware”)	1056	B.3	Hints	1103
15.3	Overview of popular microcontroller families	1059	B.4	A humble example	1103
15.3.1	On-chip peripherals	1061			
15.4	Design example 2: ac power control	1062		APPENDIX C: Resistor Types	1104
15.4.1	Microcontroller implementation	1062	C.1	Some history	1104
15.4.2	Microcontroller code	1064	C.2	Available resistance values	1104
15.5	Design example 3: frequency synthesizer	1065	C.3	Resistance marking	1105
15.5.1	Microcontroller code	1067	C.4	Resistor types	1105
15.6	Design example 4: thermal controller	1069	C.5	Confusion derby	1105
15.6.1	The hardware	1070			
15.6.2	The control loop	1074		APPENDIX D: Thévenin’s Theorem	1107

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

