

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	124
2.1.1 First transistor model: current amplifier	72		Review of Chapter 2	126
2.2 Some basic transistor circuits	73	THREE: Field-Effect Transistors	131	
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	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	Biassing 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			
4.3.5	Programmable pulse-width generator	241	FIVE: Precision Circuits		292
4.3.6	Active lowpass filter	241	5.1	Precision op-amp design techniques	292
4.4	A detailed look at op-amp behavior	242	5.1.1	Precision versus dynamic range	292
4.4.1	Departure from ideal op-amp performance	243	5.1.2	Error budget	293
4.4.2	Effects of op-amp limitations on circuit behavior	249	5.2	An example: the millivoltmeter, revisited	293
4.4.3	Example: sensitive millivoltmeter	253	5.2.1	The challenge: 10 mV, 1%, 10 MΩ, 1.8 V single supply	293
4.4.4	Bandwidth and the op-amp current source	254	5.2.2	The solution: precision RRIO current source	294
			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			

<p>5.17.5 Differential amplifier selection criteria</p> <p>Review of Chapter 5</p> <p>SIX: Filters</p> <p>6.1 Introduction</p> <p>6.2 Passive filters</p> <ul style="list-style-type: none"> 6.2.1 Frequency response with RC filters 6.2.2 Ideal performance with LC filters 6.2.3 Several simple examples 6.2.4 Enter active filters: an overview 6.2.5 Key filter performance criteria 6.2.6 Filter types 6.2.7 Filter implementation <p>6.3 Active-filter circuits</p> <ul style="list-style-type: none"> 6.3.1 VCVS circuits 6.3.2 VCVS filter design using our simplified table 6.3.3 State-variable filters 6.3.4 Twin-T notch filters 6.3.5 Allpass filters 6.3.6 Switched-capacitor filters 6.3.7 Digital signal processing 6.3.8 Filter miscellany <p>Additional Exercises for Chapter 6</p> <p>Review of Chapter 6</p> <p>SEVEN: Oscillators and Timers</p> <p>7.1 Oscillators</p> <ul style="list-style-type: none"> 7.1.1 Introduction to oscillators 7.1.2 Relaxation oscillators 7.1.3 The classic oscillator-timer chip: the 555 7.1.4 Other relaxation-oscillator ICs 7.1.5 Sinewave oscillators 7.1.6 Quartz-crystal oscillators 7.1.7 Higher stability: TCXO, OCXO, and beyond 7.1.8 Frequency synthesis: DDS and PLL 7.1.9 Quadrature oscillators 7.1.10 Oscillator “jitter” <p>7.2 Timers</p> <ul style="list-style-type: none"> 7.2.1 Step-triggered pulses 7.2.2 Monostable multivibrators 7.2.3 A monostable application: limiting pulse width and duty cycle 	<p>383</p> <p>388</p> <p>EIGHT: Low-Noise Techniques</p> <p>391</p> <p>391</p> <p>391</p> <p>393</p> <p>393</p> <p>396</p> <p>399</p> <p>400</p> <p>405</p> <p>406</p> <p>407</p> <p>407</p> <p>410</p> <p>414</p> <p>415</p> <p>415</p> <p>418</p> <p>422</p> <p>422</p> <p>423</p> <p>425</p> <p>425</p> <p>425</p> <p>428</p> <p>432</p> <p>435</p> <p>443</p> <p>450</p> <p>451</p> <p>453</p> <p>457</p> <p>457</p> <p>458</p> <p>461</p> <p>465</p> <p>7.2.4 Timing with digital counters</p> <p>Review of Chapter 7</p> <p>8.1 “Noise”</p> <ul style="list-style-type: none"> 8.1.1 Johnson (Nyquist) noise 8.1.2 Shot noise 8.1.3 $1/f$ noise (flicker noise) 8.1.4 Burst noise 8.1.5 Band-limited noise 8.1.6 Interference <p>8.2 Signal-to-noise ratio and noise figure</p> <ul style="list-style-type: none"> 8.2.1 Noise power density and bandwidth 8.2.2 Signal-to-noise ratio 8.2.3 Noise figure 8.2.4 Noise temperature <p>8.3 Bipolar transistor amplifier noise</p> <ul style="list-style-type: none"> 8.3.1 Voltage noise, e_n 8.3.2 Current noise i_n 8.3.3 BJT voltage noise, revisited 8.3.4 A simple design example: loudspeaker as microphone 8.3.5 Shot noise in current sources and emitter followers <p>8.4 Finding e_n from noise-figure specifications</p> <ul style="list-style-type: none"> 8.4.1 Step 1: NF versus I_C 8.4.2 Step 2: NF versus R_s 8.4.3 Step 3: getting to e_n 8.4.4 Step 4: the spectrum of e_n 8.4.5 The spectrum of i_n 8.4.6 When operating current is not your choice <p>8.5 Low-noise design with bipolar transistors</p> <ul style="list-style-type: none"> 8.5.1 Noise-figure example 8.5.2 Charting amplifier noise with e_n and i_n 8.5.3 Noise resistance 8.5.4 Charting comparative noise 8.5.5 Low-noise design with BJTs: two examples 8.5.6 Minimizing noise: BJTs, FETs, and transformers 8.5.7 A design example: 40¢ “lightning detector” preamp 8.5.8 Selecting a low-noise bipolar transistor 8.5.9 An extreme low-noise design challenge 	<p>465</p> <p>470</p> <p>473</p> <p>473</p> <p>475</p> <p>476</p> <p>477</p> <p>478</p> <p>478</p> <p>479</p> <p>479</p> <p>479</p> <p>480</p> <p>481</p> <p>481</p> <p>483</p> <p>484</p> <p>486</p> <p>487</p> <p>489</p> <p>489</p> <p>490</p> <p>491</p> <p>491</p> <p>491</p> <p>492</p> <p>492</p> <p>493</p> <p>494</p> <p>495</p> <p>496</p> <p>497</p> <p>500</p> <p>505</p>
-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

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{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_nC 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	594
8.11.10	Isolating input capacitance: cascoding the transimpedance amplifier	547	9.1 Tutorial: from zener to series-pass linear regulator	595
8.11.11	Transimpedance amplifiers with capacitive feedback	548	9.1.1 Adding feedback	596
8.11.12	Scanning tunneling microscope preamplifier	552	9.2 Basic linear regulator circuits with the classic 723	598
		553	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	Overshoot 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 Technologies	782
10.4.3 Combining memory and gates: sequential logic	734	11.4.2 By User Communities	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	Interrupters	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
THIRTEEN : Digital meets Analog		879	13.8.5	Analog switches in conversion applications (a detour)	916
13.1	Some preliminaries	879	13.8.6	Designs by the masters: Agilent’s world-class “multislope” converters	918
13.1.1	The basic performance parameters	879	13.9	ADCs IV: delta–sigma	922
13.1.2	Codes	880	13.9.1	A simple delta–sigma for our suntan monitor	922
13.1.3	Converter errors	880	13.9.2	Demystifying the delta–sigma converter	923
13.1.4	Stand-alone versus integrated	880	13.9.3	$\Delta\Sigma$ ADC and DAC	923
13.2	Digital-to-analog converters	881	13.9.4	The $\Delta\Sigma$ process	924
13.2.1	Resistor-string DACs	881	13.9.5	An aside: “noise shaping”	927
13.2.2	R–2R ladder DACs	882	13.9.6	The bottom line	928
13.2.3	Current-steering DACs	883	13.9.7	A simulation	928
13.2.4	Multiplying DACs	884	13.9.8	What about DACs?	930
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			
14.7.15	Controller Area Network (CAN)	1043	APPENDIX A: Math Review		1097
14.7.16	Ethernet	1045	A.1	Trigonometry, exponentials, and logarithms	1097
14.8	Number formats	1046	A.2	Complex numbers	1097
14.8.1	Integers	1046	A.3	Differentiation (Calculus)	1099
14.8.2	Floating-point numbers	1047	A.3.1	Derivatives of some common functions	1099
	Review of Chapter 14	1049	A.3.2	Some rules for combining derivatives	1100
			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			