

# CONTENTS

<b>List of Tables</b>	<b>xvii</b>		
<b>Preface to the Second Edition</b>	<b>xix</b>		
<b>Preface</b>	<b>xx</b>		
<b>ONE: Real-World Passive Components</b>	<b>1</b>		
Review of Chapter 1 of AoE3	2		
1x.1 Wire and Connectors	5		
1x.1.1 Wire gauge: resistance, heating, and current-carrying capacity	5		
1x.1.2 Stranding, insulation, and tinning	5		
1x.1.3 Printed circuit wiring	6		
1x.1.4 PCB traces	7		
<i>Resistance and current-         carrying capacity; Capacitance         and inductance; Transmission-         line impedance and attenuation</i>			
1x.1.5 Cable configurations	9		
1x.1.6 Inductance and skin effect	10		
<i>Inductance; Skin effect</i>			
1x.1.7 Capacitive and magnetic coupling	12		
1x.1.8 Mitigation of coupled signals	13		
1x.1.9 Shielded enclosures	14		
<i>Screened enclosure; A Parting         Shot</i>			
1x.1.10 Connectors	17		
1x.1.11 Connectors for RF and high-speed signals	18		
<i>An Aside: Pulse Integrity</i>			
1x.1.12 High-density connectors	21		
1x.1.13 Connector miscellany	21		
<i>Random Interlude: Our favorite solder</i>	22		
1x.2 Resistors	23		
1x.2.1 Temperature coefficient	23		
1x.2.2 Self-capacitance and self-inductance	23		
1x.2.3 Nonlinearity (voltage coefficient)	24		
		1x.2.4 Excess noise	25
		1x.2.5 Current-sense resistors and Kelvin connection	26
		1x.2.6 Power-handling capability and transient power	26
		<i>Do-it-yourself testing; Overload         to failure</i>	
		1x.2.7 Resistor dividers	29
		1x.2.8 “Digital” Resistors	31
		<i>The digipot zoo; Digipot cau-         tions; Wrapup</i>	
		<i>Random Interlude: An elegant soldering         iron</i>	36
		1x.3 Capacitors	37
		1x.3.1 Temperature coefficient	37
		1x.3.2 ESR	38
		1x.3.3 ESL	39
		1x.3.4 Dissipation factor	40
		1x.3.5 Voltage coefficient of capacitance	41
		1x.3.6 AC voltage coefficient	42
		1x.3.7 Aging	43
		1x.3.8 Frequency dependence of capacitance	43
		1x.3.9 Electromechanical self-resonance and microphonics	43
		1x.3.10 Dielectric absorption	44
		1x.3.11 Capacitor choices for typical applications	45
		<i>Bypass and decoupling; Oscilla-         tors, filters, and timing; High fre-         quency; Energy storage; AC line         filtering; High voltage</i>	
		1x.3.12 Capacitor miscellany	47
		<i>Silicon capacitors</i>	
		1x.4 Inductors	49
		1x.4.1 The basics	49
		1x.4.2 Air-core inductors	49
		<i>Solenoid – approximate; Sole-         noid – exact; Toroid; Loop</i>	

viii	Contents	<i>Art of Electronics – The x-Chapters</i>
1x.4.3	Magnetic-core inductors <i>Ferromagnetic materials; Ferrite-core solenoid; Ferrite-core toroid; Gapped core; Noise and spike suppression</i>	52
1x.4.4	Inductors and transformers for power converters	61
1x.4.5	Why <i>build</i> it, when you can <i>buy</i> it?	61
1x.4.6	Inductor examples <i>Radiofrequency “chokes” and bias-T’s</i>	62
1x.5	Poles and Zeros, and the “s-Plane”	68
1x.6	Mechanical Switches and Relays	71
1x.6.1	Why use <i>mechanical</i> switches or relays?	71
1x.6.2	So what’s the problem? <i>Relay and switch contact life; Contact protection; Relay coil suppression; Improving relay switching speed</i>	71
1x.6.3	Other switch and relay parameters <i>Switches: Function, actuator, bushing, terminals; Relays: Moving-armature, reed, and solid-state</i>	78
1x.7	Diodes	80
1x.7.1	Diode characteristics <i>The family tree; Reverse (leakage) current; Forward voltage drop; Dynamic impedance; Peak current; Reverse capacitance; Zener capacitance</i>	80
1x.7.2	Stored charge and reverse recovery <i>Reverse recovery test circuit; Dependence on reverse and forward currents; Dependence on diode size; Schottky and fast-recovery diodes; Soft-recovery diodes; Step-recovery diodes; A far-out step-recovery application: Larkin’s 40-amp kilovolt pulser; What about forward recovery?</i>	86
1x.7.3	The tunnel diode <i>Current versus voltage: Region of negative resistance; Measuring the tunnel diode characteristic curve; Tunnel diode trigger circuit</i>	92
	<i>Random Interlude: Reactance sliderule</i>	96
1x.8	Miscellaneous Circuits with Capacitors and Inductors	97
1x.8.1	Improved leading-edge detector	97
1x.8.2	Capacitance multipliers	97
	<b>TWO: Advanced BJT Topics</b>	<b>99</b>
	Review of Chapter 2 of AoE3	100
2x.1	What’s the <i>Actual</i> Leakage Current of BJTs and JFETs?	105
2x.2	Current-Source Problems and Fixes	106
2x.2.1	Improving current-source performance	106
2x.2.2	Current mirrors: multiple outputs and current ratios	108
2x.2.3	Widlar logarithmic current mirror	108
2x.2.4	Current source from Widlar mirror	109
2x.3	The Cascode Configuration	111
2x.4	BJT Amplifier Distortion: a SPICE Exploration	113
2x.4.1	Grounded-emitter amplifier	113
2x.4.2	Getting the model right	114
2x.4.3	Exploring the linearity <i>Input–output transfer function; Gain versus input</i>	115
2x.4.4	Degenerated common-emitter amplifier	117
2x.4.5	Differential amplifier <i>Estimating the distortion</i>	117
2x.4.6	Differential amplifier with emitter degeneration	119
2x.4.7	Sziklai-connected differential amplifier	120
2x.4.8	Sziklai-connected differential amplifier with current source	120
2x.4.9	Sziklai-connected differential amplifier with cascode	120

2x.4.10	Caprio's quad differential amplifier, with cascode	122	2x.12.2	High-frequency amplifiers: the ac model	145
2x.4.11	Caprio's quad with folded cascode – I	122		<i>Effects of collector voltage and current on transistor capacitances; SPICE parameters; Comparing SPICE models with measured <math>f_T</math>; Wideband micropower BJTs; Collector-base time constant and maximum oscillation frequency</i>	
2x.4.12	Caprio's quad with folded cascode – II	123	2x.12.3	A high-frequency calculation example	150
2x.4.13	Measured distortion	124	2x.13	Two-terminal Negative Resistance Circuit	151
2x.4.14	Wrapup: amplifier modeling with SPICE	124	2x.14	If It Quacks Like an Inductor ...	153
2x.5	Going Astray with SPICE: an Example	125	2x.15	Pulse Generator with Adjustable Transition Times	155
2x.6	Early Effect and Early Voltage	127	2x.15.1	Top-level view: a modernized HP-8012B	155
2x.6.1	Measuring Early effect	127	2x.15.2	Simplifying HP's output amplifier	156
2x.6.2	Some Early effect formulas	128	2x.15.3	Circuit details <i>Ramp generator; Offset circuitry; Output stage; Circuit miscellany</i>	157
2x.6.3	Consequences of Early effect: Output resistance	129	2x.15.4	Measured performance <i>Waveform generation stage; Output stage; Portrait time!</i>	160
	<i>Maximum single-stage voltage gain; Current-source output impedance</i>		2x.15.5	A simpler method	161
2x.7	The Sziklai Configuration	131	2x.16	"Designs by the Masters": $\pm 20$ V, 5 ns, 50 $\Omega$ Amplifier	163
2x.7.1	Two-transistor "standard" Sziklai	131	2x.16.1	Output stage block diagram	163
2x.7.2	Three-transistor "enhanced" Sziklai	131	2x.16.2	Output stage: the full enchilada	163
2x.7.3	Push-pull output stage: a Sziklai application	133	2x.16.3	Output stage: some fine points	165
2x.8	Bipolarity Current Mirrors	134	2x.16.4	Epilogue: 120 V, 5 A, dc-10 MHz Laboratory Amplifier	165
2x.8.1	A simple high-speed bipolarity current source	134		<i>Circuit details; Output protection; Transistor choices</i>	
	<i>Reducing input current; Operating at higher voltages</i>		<b>THREE: Advanced FET Topics</b>	<b>169</b>	
2x.8.2	Precision bipolarity current source with folded cascode	136		Review of Chapter 3 of AoE3	170
2x.9	The Emitter-Input Differential Amplifier	138	3x.1	A Guided Tour of JFETs	174
2x.9.1	An application: High-current, high-ratio current mirror	138	3x.1.1	Gate current, $I_{GSS}$ and $I_G$	179
2x.9.2	Improving the emitter-input differential amplifier	139	3x.2	A Closer Look at JFET Transconductance	182
2x.10	Transistor Beta versus Collector Current	141	3x.2.1	Dependence of $g_m$ on $I_D$	182
2x.11	Parasitic Oscillations in the Emitter Follower	143	3x.2.2	Dependence of $g_m$ on $V_{DS}$	183
2x.12	BJT Bandwidth and $f_T$	145	3x.2.3	Performance of the transconductance enhancer	183
2x.12.1	Transistor amplifiers at high frequencies: first look	145			
	<i>Reducing the effect of load capacitance</i>				

x	Contents	<i>Art of Electronics – The x-Chapters</i>
3x.2.4	Transconductance in the JFET source follower	185
3x.3	Measuring JFET Transconductance	187
3x.4	A Closer Look at JFET Output Impedance	188
3x.4.1	A JFET's $g_{os}$ -limited gain, $G_{max}$	188
3x.4.2	Source degeneration: another way to mitigate the $g_{os}$ effect	189
3x.4.3	Dependence of $g_{os}$ on drain current density	190
3x.4.4	Dependence of $g_{os}$ and $G_{max}$ on $V_{DS}$	191
3x.4.5	A parting shot: $g_{os}$ – sometimes it matters, sometimes it doesn't	191
3x.4.6	Example: A low-noise open-loop differential amplifier	191
3x.5	MOSFETs as Linear Transistors	193
3x.5.1	Output characteristics and transfer function <i>Datasheet curves; Measured data</i>	193
3x.5.2	Linear operation: hotspot SOA limitation	195
3x.5.3	Exploring the subthreshold region <i>MOSFETs at low drain voltage; MOSFETs at high drain voltage</i>	195
3x.5.4	Exploring a high-voltage MOSFET <i>IXTP1N120 transfer characteristics; IXTP1N120 transconductance</i>	198
3x.5.5	SPICE models for power MOSFETs in the subthreshold region	199
3x.5.6	Typical SPICE model for a power MOSFET <i>Equivalent circuit; Model capacitances; Other models</i>	202
3x.5.7	An unusual low-voltage MOSFET	204
3x.6	Floating High-Voltage Current Sources	206
3x.6.1	Raising output impedance with a cascode	206
3x.6.2	Reducing power dissipation	208
3x.6.3	Small-signal output impedance	208
3x.6.4	Low-cost predictable current source	209
3x.6.5	Current sources for higher voltages <i>A simple scheme; Distributed series string; Some applications: HV amplifier, HV probe; High-voltage current sources: 250 <math>\mu</math>A; High-voltage current sources: 2 mA; Current sources in high-voltage amplifiers; High-voltage current sources: 5 mA and more; Perfect high-voltage current source; Op-amp-mediated floating current source</i>	210
3x.7	Bandwidth of the Cascode; BJT versus FET	221
3x.7.1	The common-gate/common-base amplifier	221
3x.7.2	Cascode as common-gate/common-base amplifier	221
3x.7.3	Estimating cascode bandwidth	222
3x.7.4	What about MOSFETs?	222
3x.7.5	Bandwidth of the source follower	223
3x.8	Bandwidth of the Source Follower with a Capacitive Load	224
3x.8.1	Follower with resistive signal source	224
3x.8.2	Follower driven with a current signal	225
3x.9	High-Voltage Probe with High Input Impedance	228
3x.9.1	Compensated-offset MOSFET follower	228
3x.9.2	Bootstrapped op-amp follower	228
3x.10	CMOS Linear Amplifiers	232
3x.11	MOSFETs Through the Ages	234
3x.11.1	A MOSFET Saga: the First 30 Years	234
3x.11.2	The next 15 years <i>Logic-level gates; Packages; P-channel MOSFETs; High-voltage parts; Capacitances</i>	237
3x.11.3	Four kinds of power MOSFETs <i>Comparison of capacitances; Energy: what does all this capacitance stuff mean?; Conclusion</i>	243

3x.12 Measuring MOSFET Gate Charge	248	3x.21.2 High voltage, high current switches	281
3x.12.1 The gate charge curve depends on load current	248	3x.22 Precision Charge-dispensing Piezo Positioner	284
3x.12.2 Gate charge curves at constant load current	248	3x.22.1 Fast MOSFET pulsed charge dispenser	284
3x.12.3 The gate charge curve depends also on drain voltage	249	3x.22.2 Analog charge dispenser	286
3x.12.4 Gate charge test circuit	249	3x.22.3 Small-step pulsed charge dispenser	287
3x.12.5 The Miller plateau	250		
3x.13 Pulse Energy in Power MOSFETs	252	<b>FOUR: Advanced Topics in Operational Amplifiers</b>	<b>289</b>
3x.13.1 Limited only by maximum junction temperature	252	Review of Chapter 4 of AoE3	290
<i>Controlled conduction; Avalanche mode</i>		4x.1 From Philbrick to SMT	294
3x.13.2 Alternative graphs	254	A trip down memory lane.	294
3x.14 MOSFET Gate Drivers	255	4x.2 Feedback Stability and Phase Margins	296
3x.15 High-Voltage Pulsers	257	4x.2.1 Sliding $f_2$ : phase margin and circuit performance	297
3x.15.1 Two-switch +600 V pulser	257	4x.2.2 What about amplifiers with $G_{CL} > 1$ ?	298
3x.15.2 Two-switch +500 V 20 A fast pulser	259	4x.2.3 Applying Bode plots to amplifier design	298
3x.15.3 Two-switch reversible kilovolt pulser	260	4x.2.4 Afterword: High-speed op-amps	299
3x.15.4 Output monitor	260	<i>SPICEing the 3-pole op-amp</i>	
3x.15.5 Three-switch bipolarity kilovolt pulser	262	4x.3 The Bode plot: a story of three filters	301
3x.15.6 High-voltage open-ended-cable pulser	263	4x.3.1 Speedy – not!	303
<i>Random Interlude: BNC probe coupler</i>	267	4x.3.2 “insta-Bode” – exploiting the AD8302	304
3x.16 MOSFET ON-Resistance versus Temperature	268	4x.4 Transresistance Amplifiers	307
3x.17 Thyristors, IGBTs, and Wide-bandgap MOSFETs	269	4x.4.1 Stability problem	307
3x.17.1 Insulated-gate bipolar transistor (IGBT)	269	4x.4.2 Stability solution	307
3x.17.2 Thyristors	269	4x.4.3 An example: PIN diode amplifier	309
3x.17.3 Silicon carbide and gallium nitride MOSFETs	270	<i>Gaining speed; “Pedal to the metal”; Sub-picofarad capacitors</i>	
3x.18 Power Transistors for Linear Amplifiers	271	4x.4.4 A complete photodiode amplifier design	312
3x.19 Generating Fast High-Current LED Pulses	274	4x.4.5 Gain-switching	313
3x.19.1 10 ns pulser	274	4x.4.6 Some loose ends	314
3x.19.2 High-power pulser	274	4x.4.7 Optimizing the transimpedance amplifier	315
<i>Wiring; Gate voltage; Power dissipation</i>		<i>Noise–bandwidth tradeoff; An optimized three-decade TIA; Multi-range TIAs</i>	
3x.19.3 Integrated LED Drivers	276	4x.4.8 Designs by the masters: A wide-range linear transimpedance amplifier	325
3x.20 Precision 1.5 kV 1 $\mu$ s Ramp	278	4x.4.9 A “starlight-to-sunlight” linear photometer	327
3x.21 Fast Shutoff of High-Energy Magnetic Field	280		
3x.21.1 Helmholtz coils, rapid field shutoff	280		

xii	Contents	<i>Art of Electronics – The x-Chapters</i>
4x.4.10	Autoranging wideband transimpedance amplifier	332
4x.4.11	Multiple-range cascode-bootstrap wideband TIA	333
4x.5	Unity-Gain Buffers	335
4x.5.1	Stability of the composite amplifier	335
4x.5.2	Some more applications	336
4x.5.3	Some cautions	338
4x.6	High-Speed Op-amps I: Voltage Feedback	340
4x.6.1	Voltage feedback and current feedback <i>Some confusing terms</i>	340
4x.6.2	Overview of the table	341
4x.6.3	Scatterplots: Seeking trends	344
4x.7	High-speed Op-amps II: Current Feedback	352
4x.7.1	Properties of CFBs <i>Closed-loop bandwidth; Slew rate and output current; The feedback network and stability; Input current and precision</i>	352
4x.7.2	Care and feeding of CFBs	354
4x.7.3	“Hybrid” VFB+CFB op-amps	355
4x.7.4	When to use CFBs	356
4x.7.5	Mathematical postscript: bandwidth and gain in CFBs	356
4x.7.6	Remarks on the table	357
4x.8	Power Supply Rejection Ratio	360
4x.9	Capacitive-Feedback Transimpedance Amplifiers	362
4x.9.1	Capacitive-feedback TIA for gigabit optical receivers	362
4x.10	Slew Rate: A Detailed Look	364
4x.10.1	Increasing slew rate	364
4x.10.2	Case study: high-voltage pulse generator	366
4x.11	Bias-Current Cancellation	368
4x.11.1	The best of both worlds?	368
4x.11.2	Bias cancellation: the circuits <i>Simplest: Mirroring the base current of a cascode twin; Better: Bootstrapping the cascode bias; Another way: replicating the emitter current</i>	368
4x.11.3	Bias cancellation: how well does it work?	370
4x.12	Rail-to-Rail Op-amps	372
4x.12.1	Rail-to-rail inputs	372
4x.12.2	Rail-to-rail outputs	372
4x.12.3	Output near ground: when “RRO” isn’t	372
4x.12.4	Offsetting the negative supply terminal	374
4x.12.5	Designs by the masters: the Monticelli output stage	375
4x.13	Slewing and Settling	378
4x.13.1	Dependence on $f_T$ <i>Slew-rate enhanced op-amps</i>	378
4x.13.2	A caution: ‘scope overdrive artifacts	379
4x.14	Resistorless Op-amp Gain Stage	382
4x.15	Silicon Photomultipliers	384
4x.15.1	SiPM characteristics	384
4x.15.2	SiPM construction	384
4x.15.3	SiPM characteristics, electronics, and waveforms	385
4x.16	External Current Limiting	387
4x.17	Designs by the Masters: Bulletproof Input Protection	389
4x.18	Canceling Base-Current Error in the Current Source	392
4x.19	Analog “Function” Circuits	393
4x.19.1	The Lorenz attractor	393
4x.19.2	Summing amplifiers <i>Non-inverting adder; Adder-subtractor</i>	393
4x.20	Normalizing Transimpedance Amplifier	396
4x.21	Logarithmic Amplifier	398
4x.21.1	Temperature compensation of gain	398
4x.22	A Circuit Cure for Diode Leakage	400
4x.23	Capacitive Loads: Another View	401
4x.23.1	Frequency of oscillation	401
4x.23.2	So, how about a few equations?	402
4x.24	Precision High-Voltage Amplifier	404
4x.24.1	Overview	404
4x.24.2	High-voltage output stage	404
4x.24.3	Front-end amplifier stage	406
4x.24.4	Feedback stability	407
4x.24.5	Circuit capacitances and capacitive loads <i>No load, no feedback capacitance; Add feedback capacitance; Add load capacitance; Output series resistor; SPICE analysis</i>	408
4x.24.6	Output slew rate	410

<i>Art of Electronics – The x-Chapters</i>	Contents	xiii	
4x.24.7 Measured performance	410	9x.5 PWM for DC Motors	457
4x.24.8 Variations: unipolarity, higher voltages, greater speed	411	9x.5.1 The myth: PWM as secret sauce	457
<i>MOSFET transistor choices</i>		<i>An experiment; Toy trains and sewing machines; Another experiment</i>	
4x.24.9 Faster HV amplifier: 1MHz and 1200V	412	9x.5.2 Wrapup: PWM versus dc for motor drive	459
<i>Transistor choices; Circuit changes</i>		9x.5.3 Afterword: DC motor model	461
4x.24.10 High-voltage flying output switch	415	<i>Series resistance: Op-amp analogy</i>	
4x.24.11 Switched-filter application: positron–electron plasma trap	416	9x.6 Transformer + Rectifier + Capacitor = Giant Spikes!	464
4x.25 Bootstrapped Howland Current Source	418	9x.6.1 The effect	464
4x.25.1 The basic configuration	418	9x.6.2 Calculations and cures	464
4x.25.2 The full implementation	418	9x.7 Low-Voltage Clamp/Crowbar	466
4x.26 High-Voltage Bipolarity Current Source	421	9x.7.1 New clamp/crowbar	466
4x.26.1 Performance issues	422	<i>Circuit operation; Additional details; Performance</i>	
4x.27 High-Side “Current Reporter”	424	9x.8 High-Efficiency (“Green”) Switching Power Supplies	469
4x.27.1 The basic configuration	424	9x.9 Power Factor Correction (PFC)	472
4x.27.2 The full implementation	425	9x.10 High-Side High-Voltage Switching	475
4x.28 Ripple Reduction in PWM	428	9x.11 High-Side Current Sensing	477
4x.29 Nodal Loop Analysis: MOSFET Current Source	431	9x.11.1 Pulse generator overcurrent limit	477
4x.29.1 Example: MOSFET current source	431	9x.11.2 Current monitor for high-voltage amplifier	478
<i>Nodal model; KCL equations; Node equations; Results</i>		<i>Current monitor for HV bipolarity amplifier</i>	
4x.29.2 Example: Fast 2.5 A pulsed current	434	9x.12 High-Voltage Discharge Circuit	481
4x.29.3 High pulsed-current application: electroplating in a 1T magnetic field	435	9x.13 Beware Counterfeits (or, Don’t Bite into That Apple)	482
4x.30 Spectral Conversions	437	9x.14 Flashover! Creepage Visits Our Laboratory	486
4x.30.1 Octave and third-octave analysis	437	9x.15 Low-Noise Isolated Power	487
4x.30.2 Computing spectra from a time-sampled voltage	440	9x.16 Switcher Noise Suppression	492
<i>Popular window functions; Library routines can make it easy</i>		9x.16.1 Some noise-suppression measurements	492
<b>NINE: Advanced Topics in Power Control</b>	<b>444</b>	9x.16.2 Is this new?	492
Review of Chapter 9 of AoE3	445	9x.17 Inexpensive Benchtop Switcher	495
9x.1 Reverse Polarity Protection	449	9x.18 Low-Current Non-isolated DC Supplies	497
9x.2 Lithium-Ion Single-Cell Power Subsystem	450	9x.18.1 Simplest circuit: reactance-limited zener bias	497
9x.2.1 Charger features	450	9x.18.2 Improved circuit: full-wave rectifier	497
9x.2.2 Monitor and Protect	451	9x.18.3 Why hasn’t Silicon Valley responded?	498
9x.2.3 Output voltage regulator	451	9x.18.4 Case study: ceiling fan	498
9x.2.4 Multiple cells: a “battery”	452	9x.18.5 Inverse Marx generator	499
9x.3 Low-Voltage Boost Converters	453	9x.19 Bus Converter: the “DC Transformer”	502
9x.4 Foldback Current Limiting	455		

xiv	Contents	<i>Art of Electronics – The x-Chapters</i>
9x.19.1	Differences from classic switch-mode converter	502
9x.19.2	Bus converter applications	502
9x.19.3	Bus converter example	502
9x.19.4	A few comments	503
9x.20	Negative-Input Switching Converters	506
9x.20.1	Negative buck from positive boost	506
9x.20.2	Negative boost from positive buck	506
9x.21	Precision Negative Bias Supply for Silicon Photomultipliers	508
9x.22	High-Voltage Negative Regulator	510
9x.23	The Capacitance Multiplier, Revisited	511
9x.24	Precision Low-Noise Laboratory Power Supply	513
9x.24.1	Overview	513
9x.24.2	Circuit details	515
9x.24.3	Performance	516
9x.25	Lumens to Watts (Optical)	519
9x.26	Sending Power on a Beam of Light	521
9x.27	Transient Voltage Protection and Transient Thermal Response	525
9x.27.1	The problem	525
9x.27.2	The solution	525
9x.27.3	TVS devices	526
	<i>Gas surge arrestors; Metal oxide varistors; Zener TVSs</i>	
9x.27.4	MOV versus zener TVS	528
9x.27.5	“Series-mode” transient protection	529
9x.27.6	TVS circuit example	530
	<i>Fast-switching magnet</i>	
9x.27.7	Transient test circuit	531
	<i>Standard test pulses</i>	
9x.27.8	Transient thermal response	533
<b>FIFTEEN: Sensors</b>		<b>535</b>
15x.1	Distance and Displacement Sensors	537
15x.1.1	Short-range location	537
	<i>Capacitive distance sensors; Inductive distance sensors; Ultrasonic ranging; Laser triangulation; White-light interferometry; Confocal chromatic distance sensor; Laser doppler vibrometry; Fiber Bragg grating; Linear variable differential transformer (LVDT); Resonant inductive linear-displacement sensor; Optical patterned linear encoder; Magnetic patterned linear encoder; Magnetostrictive ranging; Linear Hall-sensor array; Linear potentiometer</i>	
15x.1.2	Meter-scale location	548
	<i>RF distance measurement; Optical distance measurement</i>	
15x.2	Strain Gauges and Load Cells	551
15x.2.1	Strain and strain gauges	551
15x.2.2	Load cells	551
15x.2.3	Strain gauge miscellany	554
	<i>“Apparent strain”; Strain gauge configurations; Other wrinkles</i>	
15x.2.4	Load cell: example circuit	558
15x.2.5	Strain gauge application: pressure sensor	559
15x.3	Pressure Sensors	561
15x.3.1	Pressure units	561
15x.3.2	Some pressure-sensor examples	562
	<i>Infineon DPS368 and KP235; Superior Sensor Technology ND-series; Bosch Sensortec BMP384; Sensirion SDP800-series; ESI Technology GD4200-USB; Optromix PT7; Luna os9120; Manganin resistance gauge; High pressure: Ruby fluorescence; Low pressure: Thermocouple gauge; Pirani gauge; Thermocouple gauge; Really low pressure: Hot-filament ionization gauge</i>	
15x.4	Sound and Vibration Sensors	571
15x.4.1	Microphones	571
	<i>Sound pressure units; Microphone types; Sensitivity and noise floor; Amplifiers and connectors; Recording: microphone placement</i>	

15x.4.2 Geophones and seismometers	583	15x.7.3 Thermal detectors: Thermopiles, pyroelectrics, and bolometers	625
<i>Geophones; Seismometers</i>		<i>Thermopiles; Pyroelectrics; Bolometers</i>	
15x.4.3 Accelerometers	585	15x.7.4 Photomultipliers	626
<i>Accelerometer configurations; Accelerometer noise and dyn- amic range</i>		<i>Configuration; Size and shape; Speed; Dark count, dark current; PMT bases and modules</i>	
15x.5 Temperature Sensors	589	15x.7.5 Multi-anode photomultiplier	629
15x.5.1 The finger test	589	15x.7.6 Microchannel-plate image intensifier	629
15x.5.2 Better thermometry	589	15x.7.7 Imaging detectors: CCDs and CMOS cameras	630
15x.5.3 Cryogenic temperature sensors	597	<i>CCD imagers; CMOS imagers</i>	
<i>Cryogenic sensor types; Heat flow through connecting leads</i>		15x.7.8 Streak tube	634
15x.6 Humidity Sensors	603	15x.7.9 A photosensor application: pulse oximeter	635
15x.6.1 Capacitive humidity sensors	603	<i>Complications; And solutions; Finally an inexpensive oximeter</i>	
<i>TI HDC3020; Renesas HS3001/4001, Sensirion SHT4x</i>		15x.7.10 Another photosensor application: CO <sub>2</sub> sensor	638
15x.6.2 Resistive humidity sensors	604	<i>NDIR CO<sub>2</sub> detectors; Photo- acoustic CO<sub>2</sub> detectors</i>	
15x.6.3 Optical humidity sensors	605		
15x.7 Light Sensors	606	<b>Name Index</b>	<b>641</b>
15x.7.1 Photoconductors	606	<b>Parts Index</b>	<b>643</b>
<i>How linear is the photoresis- tance?; Photoconductive opto- couplers; Infrared photoconduc- tors</i>		<b>Subject Index</b>	<b>655</b>
15x.7.2 Photodiodes and phototransistors	611		
<i>Photodetector figures-of-merit; Silicon photodiodes; Infrared photodiodes; Detectors with gain: phototransistors, APDs, SPADs, and SiPMs; Position- sensitive photodiodes</i>			