

The Art of Electronics: The x-Chapters: Second Edition

The Art of Electronics: The x-Chapters expands on topics introduced in the best selling third edition of *The Art of Electronics*, completing the broad discussions begun in the latter.

The new edition, some 30% longer than the first, has new sections on topics from very high-voltage to very low-noise, plus a whole new chapter on sensors (acceleration, displacement, distance, humidity, light, pressure, sound, strain, temperature, and vibration). *The x-Chapters* can be thought of as the essential missing pieces of *The Art of Electronics*, to be used either as its complement, or as a direct route to exploring some of the most exciting and oft-overlooked topics in advanced electronic engineering. This enticing spread of electronics wisdom and expertise will be an invaluable addition to the library of any student, researcher, or practitioner with even a passing interest in the design and analysis of electronic circuits and instruments. You'll find here techniques and circuits that are available nowhere else including topics as diverse as:

- Real components, for example: resistors (their inductance, capacitance, transient power, tempco, nonlinearity, etc.)
- Sensors – acceleration, displacement, distance, humidity, light, pressure, sound, strain, temperature, vibration
- Specialized tables, such as high-speed VFB and CFB op-amps, gate and bridge drivers, high-side switches and current-sense ICs, and more
- High-voltage low-capacitance current sources; bipolarity current mirrors
- Precision high-voltage amplifiers
- Fast high-voltage pulsed
- JFETs: a guided tour, and a closer look
- The cascode: “the aspirin of electronics”
- Power MOSFETs as linear elements, with many examples.
- Transimpedance amplifiers – bandwidth, stability, world-leading designs, and a 7-decade linear TIA
- Rail-to-rail op-amps: gremlins are lurking!
- Current-feedback amplifiers demystified
- Low-noise ultra-isolated power
- Quieting inexpensive switching power supplies: plucking gold from dross
- Noise measurements: sorting out the thicket of units, windows, and bandwidths
- Anatomy of a counterfeit iPhone charger
- BJT amplifier distortion – a deep exploration
- Sending power on a beam of light
- PWM for dc motors – a myth demolished
- Transient voltage protection and transient thermal response

Paul Horowitz is Professor of Physics and of Electrical Engineering, emeritus, at Harvard University, where in 1974 he originated the *Laboratory Electronics* course from which emerged *The Art of Electronics*. His research interests extend to topics in physics and astronomy. He is the author of some 200 scientific articles and reports, has consulted widely for industry and government, and is the designer of numerous scientific and photographic instruments.

Winfield Hill is by inclination an electronics circuit-design guru. Following a stint at Harvard's Electronics Design Center, he founded Sea Data Corporation, where he designed and built dozens of instruments for Physical Oceanography. Later he joined Edwin Land's Rowland Institute for Science (now part of Harvard University) as director of the Electronics Engineering Lab, where he has designed nearly 1000 scientific instruments.

Praise for *The Art of Electronics: The x-Chapters*

The Art of Electronics, together with *The x-Chapters*, have achieved pedagogical perfection by bending conventional approaches to knowledge transfer. The text is propelled by the authors' enthusiasm, a vast breadth of practical knowledge, and an innate sense of exactly what needs to be explained, detailed, or plotted to build true circuit intuition. *The x-Chapters* is packed with real-world details and deep-dives into advanced topics that often go unaddressed in standard curricula. The chapter on *Sensors* is alone worth the price of admission. It is a profound way to expand one's technical repertoire, yielding benefits over a lifetime and making *The x-Chapters* an essential companion to *The Art of Electronics*.

John Willison, *Founder, Stanford Research Systems*

Makers, scientists, and engineers of all stripes eventually find that they must translate their paper theories to hardware reality – and that's when they find that much of what they learned in school has limited application. Thus begins the difficult work of transforming a thought... "how can I create a robot that navigates a home?" or "is it possible to sense and classify the air quality in an underground train station?"... into sensors, motor control, data analysis, and power management.

The Art of Electronics: the x-Chapters – 2nd edition is your friend in these trying times; sitting beside you to lay out clearly the real limitations of your motor, sensor, or op-amp. It clearly explains the techniques you can use to get the best performance – no matter your budget or skill. Most engineers have to spend 30+ years of their lives behind a workbench to pick up the tips that Horowitz and Hill give to you on every page! It's an excellent companion to your reference bookshelf fave, *The Art of Electronics*.

Limor Fried ("Ladyada"), *Adafruit Industries*

In war and in peace, electronics has shaped our world. Its science, its industry, and its culture. And *The Art of Electronics* has shaped electronics. The wonderful sensors sections in *The x-Chapters* 2nd edition remind us that the world is weird and wonderful and still very analog. I have been buying *The Art of Electronics* and *The x-Chapters* in bulk to give to my engineers and interns. Buy your kids a copy and teach them to solder as well as to type.

John Larkin, *Founder, Highland Technology Inc.*

Q. What's the difference between a great junior engineer and a great senior engineer?

A. The junior engineer hasn't yet read *The x-Chapters*.

For more than a generation, *The Art of Electronics* by Paul Horowitz and Winfield Hill has defined how engineers truly learn electronics – not abstract classroom theory, but true practical understanding grounded in intuition and experimentation. *The x-Chapters* extends that tradition, equipping engineers and scientists with deep insight going beyond the basics. Keeping the attention of even the most experienced engineers, these eXtra chapters teach how to deal with pesky non-ideal characteristics to optimize designs and squeeze out that last bit of performance. Take a look at just one section – even that on "mere" wires – and you'll read the rest of the book.

Reading *The x-Chapters* is like having lunch with Paul and Win without the inhibition and constraints of a rigorous classroom. They're fun, detailed, sprinkled with wit, and tremendously useful, giving you the means to do something really great.

Jerry Branson, *Founder, The BUILD Program*

There are electronics textbooks that teach you the basics to pass exams. Then there are reference books like *The Art of Electronics* that help you master the craft of circuit design. And then there is *The Art of Electronics: the x-Chapters*, sitting alone atop the pile as the definitive grey-beard bible of deep electronics wizardry.

Dave Jones, *Founder and host of EEVBlog*

The Art of Electronics: The x-Chapters

Second Edition

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To Ava & Vida

and

Hank & Zadie

CONTENTS

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

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

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

x	Contents	Art of Electronics – The x-Chapters
	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	193
	<i>Datasheet curves; Measured data</i>	
3x.5.2	Linear operation: hotspot SOA limitation	195
3x.5.3	Exploring the subthreshold region	195
	<i>MOSFETs at low drain voltage; MOSFETs at high drain voltage</i>	
3x.5.4	Exploring a high-voltage MOSFET	198
	<i>IXTP1N120 transfer characteristics; IXTP1N120 transconductance</i>	
3x.5.5	SPICE models for power MOSFETs in the subthreshold region	199
3x.5.6	Typical SPICE model for a power MOSFET	202
	<i>Equivalent circuit; Model capacitances; Other models</i>	
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	210
	<i>A simple scheme; Distributed series string; Some applications: HV amplifier, HV probe; High-voltage current sources: 250 μA; 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>	
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	237
	<i>Logic-level gates; Packages; P-channel MOSFETs; High-voltage parts; Capacitances</i>	
3x.11.3	Four kinds of power MOSFETs	243
	<i>Comparison of capacitances; Energy: what does all this capacitance stuff mean?; Conclusion</i>	

<i>Art of Electronics – The x-Chapters</i>		Contents	xi
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	FOUR: Advanced Topics in Operational Amplifiers	289
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 μ 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	Art of Electronics – The x-Chapters
	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	340
	<i>Some confusing terms</i>	
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	352
	<i>Closed-loop bandwidth; Slew rate and output current; The feedback network and stability; Input current and precision</i>	
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	368
	<i>Simplest: Mirroring the base current of a cascode twin; Better: Bootstrapping the cascode bias; Another way: replicating the emitter current</i>	
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	378
	<i>Slew-rate enhanced op-amps</i>	
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	393
	<i>Non-inverting adder; Adder–subtractor</i>	
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	408
	<i>No load, no feedback capacitance; Add feedback capacitance; Add load capacitance; Output series resistor; SPICE analysis</i>	
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
4x.24.9 Faster HV amplifier: 1MHz and 1200V	412	<i>An experiment; Toy trains and sewing machines; Another experiment</i>	
4x.24.10 High-voltage flying output switch	415	9x.5.2 Wrapup: PWM versus dc for motor drive	459
4x.24.11 Switched-filter application: positron–electron plasma trap	416	9x.5.3 Afterword: DC motor model	461
4x.25 Bootstrapped Howland Current Source	418	<i>Series resistance: Op-amp analogy</i>	
4x.25.1 The basic configuration	418	9x.6 Transformer + Rectifier + Capacitor = Giant Spikes!	464
4x.25.2 The full implementation	418	9x.6.1 The effect	464
4x.26 High-Voltage Bipolarity Current Source	421	9x.6.2 Calculations and cures	464
4x.26.1 Performance issues	422	9x.7 Low-Voltage Clamp/Crowbar	466
4x.27 High-Side “Current Reporter”	424	9x.7.1 New clamp/crowbar	466
4x.27.1 The basic configuration	424	<i>Circuit operation; Additional details; Performance</i>	
4x.27.2 The full implementation	425	9x.8 High-Efficiency (“Green”) Switching Power Supplies	469
4x.28 Ripple Reduction in PWM	428	9x.9 Power Factor Correction (PFC)	472
4x.29 Nodal Loop Analysis: MOSFET Current Source	431	9x.10 High-Side High-Voltage Switching	475
4x.29.1 Example: MOSFET current source	431	9x.11 High-Side Current Sensing	477
<i>Nodal model; KCL equations; Node equations; Results</i>		9x.11.1 Pulse generator overcurrent limit	477
4x.29.2 Example: Fast 2.5 A pulsed current	434	9x.11.2 Current monitor for high-voltage amplifier	478
4x.29.3 High pulsed-current application: electroplating in a 1T magnetic field	435	<i>Current monitor for HV bipolarity amplifier</i>	
4x.30 Spectral Conversions	437	9x.12 High-Voltage Discharge Circuit	481
4x.30.1 Octave and third-octave analysis	437	9x.13 Beware Counterfeits (or, Don’t Bite into That Apple)	482
4x.30.2 Computing spectra from a time-sampled voltage	440	9x.14 Flashover! Creepage Visits Our Laboratory	486
<i>Popular window functions; Library routines can make it easy</i>		9x.15 Low-Noise Isolated Power	487
NINE: Advanced Topics in Power Control	444	9x.16 Switcher Noise Suppression	492
Review of Chapter 9 of AoE3	445	9x.16.1 Some noise-suppression measurements	492
9x.1 Reverse Polarity Protection	449	9x.16.2 Is this new?	492
9x.2 Lithium-Ion Single-Cell Power Subsystem	450	9x.17 Inexpensive Benchtop Switcher	495
9x.2.1 Charger features	450	9x.18 Low-Current Non-isolated DC Supplies	497
9x.2.2 Monitor and Protect	451	9x.18.1 Simplest circuit: reactance-limited zener bias	497
9x.2.3 Output voltage regulator	451	9x.18.2 Improved circuit: full-wave rectifier	497
9x.2.4 Multiple cells: a “battery”	452	9x.18.3 Why hasn’t Silicon Valley responded?	498
9x.3 Low-Voltage Boost Converters	453	9x.18.4 Case study: ceiling fan	498
9x.4 Foldback Current Limiting	455	9x.18.5 Inverse Marx generator	499
		9x.19 Bus Converter: the “DC Transformer”	502

xiv	Contents	Art of Electronics – The x-Chapters
	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
	FIFTEEN: Sensors	535
	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>	

<i>Art of Electronics – The x-Chapters</i>		Contents	xv
15x.4.2 Geophones and seismometers	583	15x.7.3 Thermal detectors: Thermopiles, pyroelectrics, and bolometers	625
15x.4.3 Accelerometers	585	<i>Thermopiles; Pyroelectrics; Bolometers</i>	
15x.5 Temperature Sensors	589	15x.7.4 Photomultipliers	626
15x.5.1 The finger test	589	<i>Configuration; Size and shape; Speed; Dark count, dark current; PMT bases and modules</i>	
15x.5.2 Better thermometry	589	15x.7.5 Multi-anode photomultiplier	629
15x.5.3 Cryogenic temperature sensors	597	15x.7.6 Microchannel-plate image intensifier	629
<i>Cryogenic sensor types; Heat flow through connecting leads</i>		15x.7.7 Imaging detectors: CCDs and CMOS cameras	630
15x.6 Humidity Sensors	603	<i>CCD imagers; CMOS imagers</i>	
15x.6.1 Capacitive humidity sensors	603	15x.7.8 Streak tube	634
<i>TI HDC3020; Renesas HS3001/4001, Sensirion SHT4x</i>		15x.7.9 A photosensor application: pulse oximeter	635
15x.6.2 Resistive humidity sensors	604	<i>Complications; And solutions; Finally an inexpensive oximeter</i>	
15x.6.3 Optical humidity sensors	605	15x.7.10 Another photosensor application: CO ₂ sensor	638
15x.7 Light Sensors	606	<i>NDIR CO₂ detectors; Photo- acoustic CO₂ detectors</i>	
15x.7.1 Photoconductors	606		
<i>How linear is the photoresis- tance?; Photoconductive opto- couplers; Infrared photoconduc- tors</i>		Name Index	641
15x.7.2 Photodiodes and phototransistors	611	Parts Index	643
<i>Photodetector figures-of-merit; Silicon photodiodes; Infrared photodiodes; Detectors with gain: phototransistors, APDs, SPADs, and SiPMs; Position- sensitive photodiodes</i>		Subject Index	655

LIST OF TABLES

Table 1x.1. Copper Wire Table.	6	Table 4x.1. Unity-Gain Buffers.	338
Table 1x.2. Selected PCB Transmission Lines.	9	Table 4x.2. High-Speed Op-amps I: VFB.	348
Table 1x.3. RF Connectors, Approximate $f_{\max}$.	19	Table 4x.3. High-Speed Op-amps II: CFB.	358
Table 1x.4. EIA Temperature Coefficient Codes for Class I Ceramic Dielectric Capacitors.	37	Table 4x.4. Slew Rate and Settling Time of Selected Op-amps.	380
Table 1x.5. EIA Temperature Characteristic Codes for Class II & III Ceramic Dielectric Capacitors.	39	Table 4x.5. HV MOSFET Choices.	413
Table 1x.6. Conversion Factors Between SI and CGS.	49	Table 4x.6a. Conversion Table for Spectral Units.	438
Table 1x.7. Relay Coil Suppression Measurements.	77	Table 4x.6b. Conversion Table of Equations for Spectral Units.	439
Table 2x.1. Bandwidth and Capacitance of Selected Discrete BJTs.	149	Table 4x.7. Octave and 1/3 Octave Bands.	440
Table 3x.1. Junction Field-Effect Transistors (JFETs).	175	Table 4x.8. DFT Window Parameters.	443
Table 3x.2. JFET Amplifier Gain Tests.	190	Table 9x.1. Small Transformer Parasitics.	465
Table 3x.3. High-voltage Amplifier MOSFETs.	200	Table 9x.2. Selected High-Side Switches.	476
Table 3x.4. Low-Side MOSFET Gate Drivers.	256	Table 9x.3. High-Side Current-Sensing ICs.	480
Table 3x.5. High-Voltage Half-Bridge Drivers.	263	Table 9x.4. Photopic Luminous Efficiency.	520
Table 3x.6. Representative Power-Amplifier Transistors.	271	Table 15x.1. Sensor Sections in Previous Editions.	536
		Table 15x.2. Pressure Units Conversion.	562
		Table 15x.3. Thermometry Methods.	597
		Table 15x.4. Cryogenic Temperature Sensors.	599
		Table 15x.5. Photoconductive Optocouplers.	609

PREFACE TO THE SECOND EDITION

In this second edition we continue the mix of electronics “short stories” and longer substantive narratives. For the former we’ve indulged our curiosity unashamedly, with new chapter sections on topics wandering from the very high voltage (pulse generator; step-and-hold generator; flying Howland current source; dramatic powerline “flashover”) to the very low noise (can feedback really quiet transistor and voltage-reference noise? how well do screened enclosures work?). Some new topics were propelled by the availability of ridiculously low-priced test equipment (would you believe, 300 W half-rack benchtop regulated power supplies for less than \$50? the bad news – they’re terribly noisy, but the good news – they’re easily quieted); or by the enhanced capabilities of ordinary oscilloscopes (automated Bode plots). Longer chapter sections expand on previous obsessions (transimpedance amplifiers whose noise and bandwidth properties extend by an order of magnitude the performance of the best commercially available units), or chronic annoyances (converting among the many different units associated with noise measurements).

But perhaps the new material with the most impact is likely to be a new and detailed 100-page chapter on “Sensors” (acceleration, displacement, distance, humidity, light, pressure, sound, strain, temperature, and vibration), important topics curiously absent from the main volume and the first edition of these quirky (but lovable) x-Chapters. Altogether these additions expand the book by some 30%. While we were at it, we achieved another 25% expansion by abandoning the annoyingly thin paper stock of the first edition: the thing now looks and feels like a proper 700-page book! We’re pleased with it, and hope you will be too.

As with the first edition, we are seriously indebted to the usual suspects, most prominently to David Tranah, our talented and fearless editor, and to Jim MacArthur, master circuit designer and lightning-quick implementer. Added to the cast, for this new edition, are David Ely, Earl Hergert, Graham Keeth, David Mindell, and Alan Stern. They all aimed to keep us on the straight path; to the extent we’ve wandered, blame us, not them. And, please, tell us of our

transgressions, so we can fix them in later printings and editions.

* * * * *

Finally, it is our duty to remind you of the *Legal Notice* appended to the preface of the first edition, on page xxii.

Paul Horowitz
Winfield Hill
January 2026
Cambridge, Massachusetts

PREFACE

Why the “x-Chapters”? Simple answer: they are the eXtra Chapters that couldn’t be shoehorned into the 1250-page third edition of *The Art of Electronics*; they are the completion of the broad discussions begun in the latter.

But that’s too simple. First some background: We’re often asked “is your book *The Art of Electronics* (AoE) a textbook, or is it a reference book?” to which we answer “yes.” Although it originated as a handwritten samizdat-style set of course notes¹ for a newly-born circuit-design course in laboratory electronics at Harvard in 1974, it has acquired a majority readership among circuit designers, both professional and, increasingly, among the happily growing ranks in the self-taught maker community.

There’s an inherent tension between the text and reference book structures: a textbook should lay out its subject in a logical progression, whereas a reference book should treat topics as capsules. For example, in AoE we visit and revisit the subject of current sources successively as new tools come to hand: in Chapter 1 we use a voltage source in series with a resistor; in the next chapter we use BJTs with emitter resistors (simple version, then V_{BE} compensated, then the Wilson mirror or cascode to defeat Early effect); in Chapter 3 it’s no surprise that we make current sources with FETs and with hybrid BJT–FET configurations; Chapter 4 provides the powerful op-amp tool to create precision currents sources, a topic that continues in the following chapter on precision design. It doesn’t stop there – in Chapter 7 we see more current sources (this time in connection with sawtooth oscillators); in the power chapter (9) they’re back (hijacked 3-terminal regulators); and of course they can’t resist a cameo appearance in the conversion chapter (13), as digitally-programmable precision sources, nanoamp sources, high-voltage floating sources, coil-driving sources, and more.

That structure, good for class- and self-study, is sub-optimal for someone with plenty of electronics background who needs to design a current source and needs to balance the engineering tradeoffs. For a challenge like that, a better choice would be a (reference) book with a sec-

tion called *Current Source Design*. Our initial plans for the third edition of AoE included a set of chapter annexes, the x-Chapters,² which would capture advanced topics and applications in a less linear style. But including such annexes seemed awkward, and anyway by the time the book had reached 1200 pages (without the x-chapters) it was clear we needed to peel off the latter as a supplementary volume. We did keep a handful of advanced topics in AoE3, largely in Chapters 5 and 8 (Precision Circuits, Low-Noise Techniques), but this new annex includes all the advanced material that we had targeted for Chapters 1, 2, 3, 4, and 9 (with corresponding numbering).

Now for *The x-Chapters*: Freed from the constraints of linear textbook-style organization, we’ve written these like a set of short stories, on topics that are, variously, advanced, important, novel, or just plain fun. We think of them as little gems, a collection of “pearls of electronics” (our editor’s suggested title). As such, they are different in character from the topics of the main volume, AoE3.

Here are some examples, from the nearly 100 major topic headings:

- wiring: skin effect, coupling, shielding, PCB impedance
- resistors and capacitors: nonlinearity, tempco, parasitics, pulse endurance, and more
- inductors demystified (at last!); cores, gapping, and all that. . .
- simplified treatment of poles, zeros, and the s -plane
- switches and relays: contact degradation, dry switching, coil driving, and more
- diodes: leakage, reverse recovery, step-recovery, tunnel diodes
- bipolarity current mirrors
- what is the *actual* leakage current of BJTs and JFETs?
- BJT amplifier distortion: a SPICE exploration
- parasitic oscillation in the emitter follower
- why the emitter follower output looks inductive

² But also, in a nod to Mulder and Scully, a suggestion that “the truth is in there.”

- designs by the masters:
 - (a) ± 20 V, 5 ns, $50\ \Omega$ amplifier
 - (b) bulletproof input protection
 - (c) the Monticelli output stage
 - (d) wide-range (7-decade) linear transimpedance amplifier
- JFETs: a guided tour, and a closer look
- MOSFETs as linear transistors; CMOS linear amplifiers
- depletion-mode MOSFET current sources
- high-voltage, low-capacitance current sources
- pulse energy in power MOSFETs
- MOSFET gate drivers
- high-voltage pulsers
- high-voltage probe with $>1\text{G}\Omega$ input impedance
- IGBTs and other power semiconductors
- low-voltage switching: MOS vs BJT
- op-amp history: from Philbrick to SMT
- feedback stability and phase margin
- bias-current cancellation in BJT-input op-amps
- transimpedance amplifiers – bandwidth and stability
- precision high-voltage amplifier
- ratio (normalizing) transimpedance amplifier
- unity-gain buffers
- current-feedback amplifiers demystified
- the gotchas of rail-to-rail op-amps
- silicon photomultipliers
- analog function circuits – the Lorenz attractor
- high-voltage bipolarity current source
- ripple reduction in PWM
- reverse-polarity protection
- transformer + rectifier + capacitor = giant spikes!
- low-voltage clamp/crowbar
- high-efficiency (“green”) power switching power supplies
- power-factor correction
- high-side current sensing
- the “dc transformer” (bus converter)
- beware counterfeit chargers (or, don’t bite into *that* Apple!)
- low-noise ultra-isolated power
- negative-input switching converters
- precision negative bias supply for silicon photomultipliers
- high-voltage negative regulator
- precision low-noise laboratory power supply
- PWM for dc motors – a myth demolished
- sending power on a beam of light
- fast LED pulsers
- “it’s too hot” redux – many methods of thermometry

- transient voltage protection and transient thermal response
- low-capacitance MOSFET-gate protection
- charge-dispensing piezo positioner
- precision 1500 V 1 microsecond ramp
- fast shutoff of high-energy magnetic field

We hope these will appeal to a varied audience. We enjoyed experimenting with their circuits, and finding a way to set down on paper the essential and digestible takeaway. *Bon appetit!*

Acknowledgments

Once again topping the list of people to whom we owe a giant debt of gratitude is David Tranah, our indefatigable editor: he is our linchpin, our helpful $\text{\LaTeX}$ expert, our wise advisor of all things bookish, and (would you believe?) our *compositor*! He put up with a pair of fussy authors, and he hosted us in a fine visit to the Cambridge University Press mother-ship.

We are grateful to Jim Macarthur, circuit designer extraordinaire, for his careful reading of chapter drafts, and invariably helpful suggestions for improvement; we adopted every one. Our colleague Peter Lu taught us the delights of Adobe Illustrator, and appeared at a moment’s notice when we went off the rails; the book’s figures are testament to the quality of his tutoring. We are indebted to Mike Burns for his careful reading, and careful computation of thorny functions.

For their many helpful contributions we thank Steve Cerwin, Tom Hayes, Phil Hobbs, Peter Horowitz, John Larkin, Maggie McFee, Ali Mehmed, and Jim Thompson. We thank also others whom (we’re sure) we’ve here overlooked, with apologies for the omission. Additional contributors to the book’s content (circuits, inspired web-based tools, unusual measurements, etc., from the likes of Keith Billings, Kent Lundberg, and Steve Woodward) are referenced throughout the book in the relevant text.

In the production chain we are indebted to our copy editor Jon Billam for his light but precise touch, and a cast of unnamed graphic artists who converted our pencil circuit sketches into beautiful vector graphics.

And finally, we are forever indebted to our loving, supportive, and ever-tolerant spouses Vida and Ava, Vida and Ava, who suffered through decades of abandonment as we obsessed over every detail of our *third* encore.

Paul Horowitz
 Winfield Hill
 August 2019
 Cambridge, Massachusetts

Legal notice

In this book we have attempted to teach the techniques of electronic design, using circuit examples and data that we believe to be accurate. However, the examples, data, and other information are intended solely as teaching aids and should not be used in any particular application without independent testing and verification by the person making the application. Independent testing and verification are especially important in any application in which incorrect functioning could result in personal injury or damage to property.

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