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978-1-009-63288-1 — The Art of Electronics: The x-Chapters 2nd Edition
Paul Horowitz , Winfield Hill
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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 pulsers
- 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

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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 e*X*tra 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 notes[1] 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 suboptimal 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 section 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

[1] See for yourself: https://artofelectronics.net/prehistory/.

[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 Ω amplifier
  - (b) bulletproof input protection
  - (c) the Monticelli ouput 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 >1GΩ 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 appetít!*

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 LaTeXpert, 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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