Learning the Art of Electronics

This introduction to circuit design is unusual in several respects.

First, it offers not just explanations, but a full lab course. Each of the 25 daily sessions begins with a discussion of a particular sort of circuit followed by the chance to try it out and see how it actually behaves. Accordingly, students understand the circuit's operation in a way that is deeper and much more satisfying than the manipulation of formulas.

Second, it describes circuits that more traditional engineering introductions would postpone: thus, on the third day, we build a radio receiver; on the fifth day, we build an operational amplifier from an array of transistors. The digital half of the course centers on applying microcontrollers, but gives exposure to Verilog, a powerful Hardware Description Language.

Third, it proceeds at a rapid pace but requires no prior knowledge of electronics. Students gain intuitive understanding through immersion in good circuit design.

- Each session is divided into several parts, including Notes, Labs; many also have Worked Examples and Supplementary Notes
- An appendix introducing Verilog
- Further appendices giving background facts on oscilloscopes, Xilinx, transmission lines, pinouts, programs etc, plus advice on parts and equipment
- Very little math: focus is on intuition and practical skills
- A final chapter showcasing some projects built by students taking the course over the years

Thomas C. Hayes reached electronics via a circuitous route that started in law school and eventually found him teaching Laboratory Electronics at Harvard, which he has done for thirty-five years. He has also taught electronics for the Harvard Summer School, the Harvard Extension School, and for seventeen years in Boston University's Department of Physics. He shares authorship of one patent, for a device that logs exposure to therapeutic bright light. He and his colleagues are trying to launch this device with a startup company named Goodlux Technologies. Tom designs circuits as the need for them arises in the electronics course. One such design is a versatile display, serial interface and programmer for use with the microcomputer that students build in the course.

Paul Horowitz is a Research Professor of Physics and of Electrical Engineering at Harvard University, where in 1974 he originated the Laboratory Electronics course from which emerged *The Art of Electronics*.

Learning the Art of Electronics

A Hands-On Lab Course

Thomas C. Hayes

with the assistance of Paul Horowitz

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For Debbie, Tessa, Turner and Jamie

And in memory of my beloved friend, Jonathan

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Preface

A book and a course

This is a book for the impatient. It's for a person who's eager to get at the fun and fascination of putting electronics to work. The course squeezes what we facetiously call "all of electronics" into about twenty-five days of class. Of course, it is nowhere near *all*, but we hope it is enough to get an eager person launched and able to design circuits that do their tasks well.

Our title claims that this volume, which obviously is a *book*, is also a *course*. It is that, because it embodies a class that Paul Horowitz and I taught together at Harvard for more than 25 years. It embodies that course with great specificity, providing what are intended as day-at-a-time doses.

A day at a time: Notes, Lab, Problems, Supplements

Each day's dose includes not only the usual contents of a *book* on electronics – notes describing and explaining new circuits – but also a *lab* exercise, a chance to try out the day's new notions by building circuits that apply these ideas. We think that building the circuits will let you understand them in a way that reading about them cannot.

In addition, nearly every day includes a *worked example* and many days include what we call "supplementary notes." These – for example, early notes on how to read resistors and capacitors – are not for every reader. Some people don't need the note because they already understand the topic. Others will skip the note because they don't want to invest the time on a first pass through the book. That's fine. That's just what we mean by "supplementary:" it's something (like a supplementary vitamin) that may be useful, but that you can quite safely live without.

What's new?

If any reader is acquainted with the *Student Manual...*, published in 1989 to accompany the second edition of *The Art of Electronics*, it may be worth noting principal differences between this book and that one. First, this book means to be self-sufficient, whereas the earlier book was meant to be read alongside the larger work. Second, the most important changes in content are these:

- Analog:
  - we devote a day primarily to the intriguing and difficult topic of *parasitic* oscillations and their cures;
  - we give a day to building a "PID" circuit, stabilizing a feedback loop that controls a motor's position. We apply signals that form three functions of an *error* signal, the difference between target voltage and output voltage: "Proportional" (P), "Integral" (I), and "Derivative" (D) functions of that difference.

- Digital:
  - application of Programmable Logic Devices (PLDs or "PALs"), programmed with the high-level *hardware description language* (HDL), Verilog;
  - a shift from use of a microprocessor to a *microcontroller*, in the computer section that concludes the course. This microcontroller, unlike a microprocessor, can operate with little or no additional circuitry, so it is well-suited to the construction of useful devices rather than computers.
- Website: The book's website `learningtheartofelectronics.com` has a lot more things, in particular code in machine readable form. Appendix H lists these.

. . . And the style of this book

A reader will gather early on that this book, like the *Student Manual* is strikingly informal. Many figures are hand-drawn; notation may vary; explanations aim to help intuition rather than to offer a mathematical view of circuits. We emphasize *design* rather than *analysis*. And we try hard to devise applications for circuits that are fun: we like it when our designs make sounds (on a good day they emit *music*), and we like to see motors spin.

Who's likely to enjoy this book and course

You need not resemble the students who take our course at the university, but you may be interested to know who they are, since the course evolved with them in mind. We teach the course in three distinct forms. Most of our students take it during fall and spring daytime classes at the College. There, about half are undergraduates in the sciences and engineering; the other half are graduate students, including a few cross-registered from MIT who need an introduction quicker (and, admittedly, less deep) than electronics courses offered down there. (We don't get EE majors from there; we get people who want a less formal introduction to the subject.)

In the night version of the course, we get mostly older students, many of whom work with technology and who have become curious about what's in the "box" that they work with. Most often the mysterious "box" is simply a computer, and the student is a programmer. Sometimes the "box" is a lab setup (we get students from medical labs, across the river), or an industrial control apparatus that the student would like to demystify.

In the summer version of the course, about half our students are rising high school seniors – and the ablest of these prove a point we've seen repeatedly: to learn circuit design you don't need to know any substantial amount of physics or sophisticated math. We see this in the College course, too, where some of our outstanding students have been Freshmen (though most students are at least two or three years older).

And we can't help boasting, as we did in the preface to the 1989 *Student Manual*, that once in a great while a professor takes our course, or at least sits in. One of these buttonholed one of us recently in a hallway, on a visit to the University where he was to give a talk. "Well, Tom," he said, "one of your students finally made good." He was modestly referring to the fact that he'd recently won a Nobel Prize. We wish we could claim that we helped him get it. We can't. But we're happy to have him as an alumnus.[1]

We expect that some of these notes will strike you as elementary, some as excessively dense: your

[1] This was Frank Wilczek. He did sit quietly at the back of our class for a while, hoping for some insights into a simulation that he envisioned. If those insights came, they probably didn't come from us.

reaction naturally will reflect the uneven experience you have had with the topics we treat. Some of you are sophisticated programmers, and will sail through the assembly-language programming near the course's end; others will find it heavy going. That's all right. The course out of which this book grew has a reputation as fun, and not difficult in one sense, but difficult in another: the concepts are straightforward; abstractions are few. But we do pass a lot of information to our students in a short time; we do expect them to achieve literacy rather fast. This course is a lot like an introductory language course, and we hope to teach by the method sometimes called immersion. It is the laboratory exercises that do the best teaching; we hope this book will help to make those exercises instructive. I have to add though, in the spirit of modern jurisprudence, a reminder to read the legal notice appended to this Preface.

The mother ship: Horowitz & Hill's The Art of Electronics

Paul Horowitz launched this course, 40-odd years ago, and he and Winfield Hill wrote the book that, in its various editions, has served as textbook for this course. That book, now in its third edition and which we will refer to as "AoE," remains the reference work on which we rely. We no longer require that students buy it as they take our course. It is so rich and dense that it might cause intellectual indigestion in a student just beginning his study of electronics. But we know that some of our students and readers will want to look more deeply into topics treated in this book, and to help those people we provide cross-references to AoE throughout this book. The fortunate student who has access to AoE can get more than this book by itself can offer.

Analog and digital: a possible split

In our College course we go through all the book's material in one term of about thirteen weeks. In the night course, which meets just once each week, we do the same material in two terms. The first term treats analog (Days 1–13), the second treats digital (Days 14–26). We know that some other universities use the same split, analog versus digital. It is quite possible to do the digital half before the analog. Only on the first day of digital – when we ask that people build a logic gate from MOSFET switches – would a person without analog training need a little extra guidance. For the most part, the digital half treats its devices as black boxes that one need not crack open and understand. We do need to be aware of input and output properties, but these do not raise any subtle analog questions

It is also possible to pare the course somewhat, if necessary. We don't like to see any of our labs missed, but we know that the summer version of the class, which compresses it all into a bit more than six weeks, makes the tenth lab optional (Day 10 presents a "PID" motor controller). And the summer course omits the gratifying but not-essential digital project lab, 20L, in which students build a device of their own design.

Who helped especially with this book

First, and most obviously, comes Paul Horowitz, my teacher long ago, my co-teacher for so many years, and all along a demanding and invaluable critic of the book as it evolved. Most of the book's hand-drawn figures, as well, still are his handiwork. Without Paul and his support, this book would not exist.

Second, I want to acknowledge the several friends and colleagues who have looked closely at parts of the book and have improved and corrected these parts. Two are friends with whom I once taught,

and who thus not only are expert in electronics but also know the course well. These are Steve Morss and Jason Gallicchio. Steve and I taught together nearly thirty years ago. Back then, he helped me to try out and to understand new circuits. He then went off to found a company, but we stayed in touch, and when we began to use a logic compiler in the course (Verilog) I took advantage of his experience. Steve was generous with his advice and then with a close reading of our notes on the subject. As I first met Verilog's daunting range of powers it was very good to be able to consult a patient and experienced practitioner.

Jason helped especially with the notes on sampling. He has the appealing but also intimidating quality of being unable to give half-power, light criticism. I was looking for pointers on details. The draft of my notes came back glowing red with his astute markups. I got more help than I'd hoped for – but, of course, that was good for the notes.

A happy benefit of working where I do is to be able to draw on the extremely knowledgeable people about me, when I'm stumped. Jim MacArthur runs the electronics shop, here, and is always overworked. I could count on finding him in his lab on most weekends, and, if I did, he would accept an interruption for questions either practical or deep. David Abrams is a similarly knowledgeable colleague who twice has helped me to explain to students results that I and the rest of us could not understand. With experience in industry as well as in teaching our course, David is another specially valuable resource.

Curtis Mead, one of Paul Horowitz's graduate students, gave generously of his skill in circuit layout, to help us make the LCD board that we use in the digital parts of this course. Jake Connors, who had served as our teaching assistant, also helped to produce the LCD boards that Curtis had laid out. Randall Briggs, another of our former TAs, helped by giving a keen, close reading.

It probably goes without saying, but let's say it: whatever is wrong in this book, despite the help I've had, is my own responsibility, my own contribution, not that of any wise advisor.

In the laborious process of producing readable versions of the book's thousand-odd diagrams, two people gave essential help. My son, Jamie Hayes, helped first by drawing, and then by improving the digital images of scanned drawings. Ray Craighead, a skilled illustrator whom we found online,[2] made up intelligently rendered computer images from our raggedy hand-drawn originals. He was able to do this in a style that does not jar too strikingly when placed alongside our many hand-drawn figures. We found no one else able to do what Ray did.

Then, when the pieces were approximately assembled, but still very ragged, the dreadfully hard job of putting the pieces together, finding inconsistencies and repetitions, cutting references to figures that had been cut, attempting to impose some consistency, ("Carry_Out" rather than "$\text{Carry}_{\text{OUT}}$" or "$C_{\text{out}}$" – at least on the same page – and so on), in 1000 pages or so, fell to my editor, David Tranah. He put up not only with the initial raggedness, but also with continual small changes, right to the end, and he did this soon after he had completed a similarly exhausting editing of AoE. For this unflagging effort I am both admiring and grateful.

And, finally, I should thank my wife, Debbie Mills, for tolerating the tiresome sight of me sitting, distracted, in many settings – on back porch, vacation terrace in Italy, fireside chair – poking away at revisions. She will be glad that the book, at last, is done.

[2] See craighead.com.

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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Overview, as the Course begins

The circuits of the first three days in this course are humbler than what you will see later, and the devices you meet here are probably more familiar to you than, say, transistors, operational amplifiers – or microprocessors: Ohm's Law will surprise none of you; $I = CdV/dt$ probably sounds at least vaguely familiar.

But the circuit elements that this section treats – passive devices – appear over and over in later active circuits. So, if a student happens to tell us, "I'm going to be away on the day you're doing Lab 2," we tell her she will have to make up the lab somehow. We tell her that the second lab, on *RC* circuits, is the most important in the course. If you do not use that lab to cement your understanding of *RC* circuits – especially filters – then you will be haunted by muddled thinking for at least the remainder of the analog part of the course.

Resistors will give you no trouble; diodes will seem simple enough, at least in the view that we settle for: they are one-way conductors. Capacitors and inductors behave more strangely. We will see very few circuits that use inductors, but a great many that use capacitors. You are likely to need a good deal of practice before you get comfortable with the central facts of capacitors' behavior – easy to state, hard to get an intuitive grip on: they pass AC, block DC, and only *rarely* cause large phase shifts.

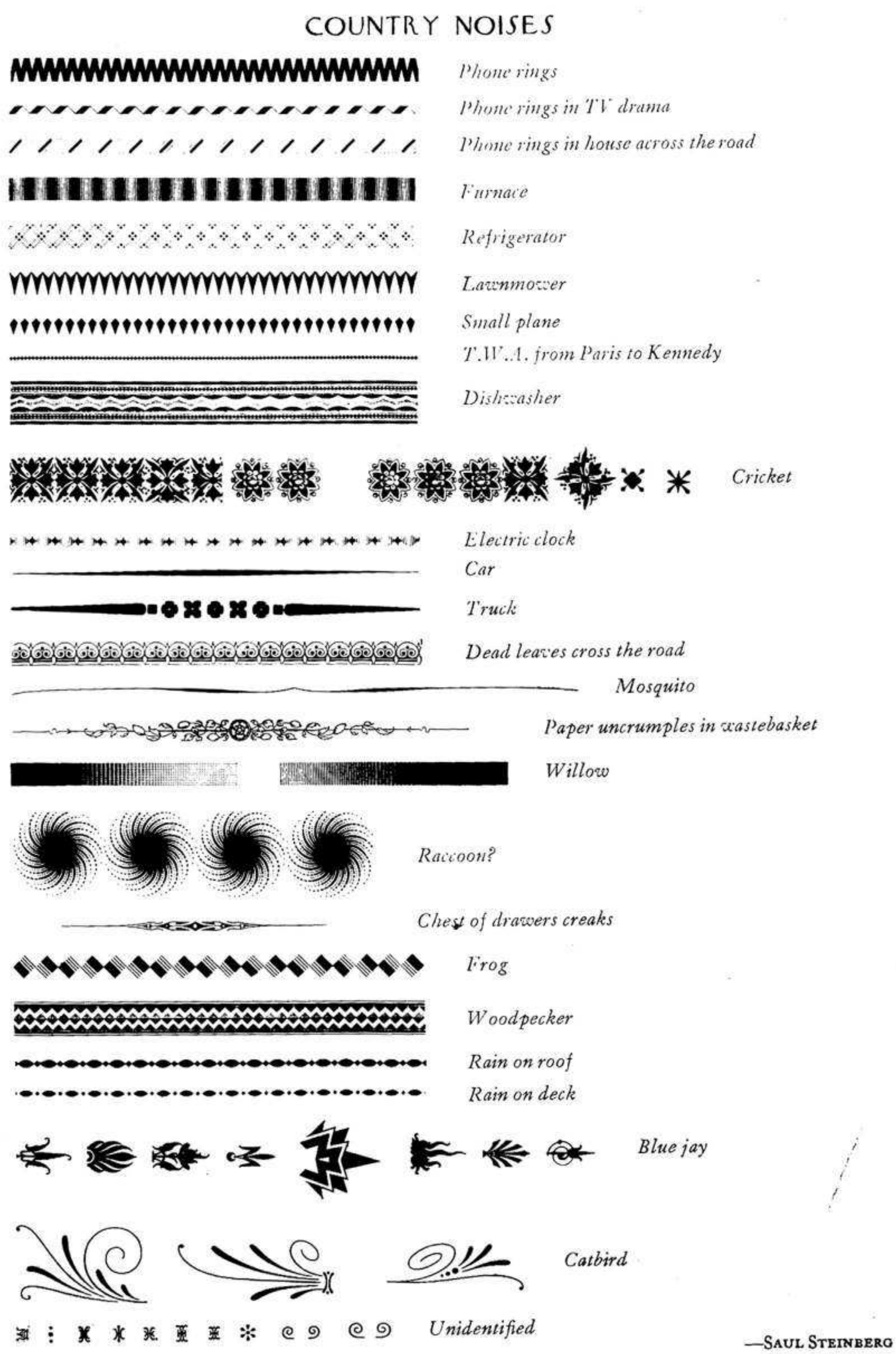
We should also restate a word of reassurance: you can manage this course perfectly even if the "$-j$" in the expression for the capacitor's impedance is completely unfamiliar to you. If you consult AoE, and after reading about complex impedances in AoE's spectacularly dense Math Review (Appendix A) you feel that you must be spectacularly dense, don't worry. That is the place in the course where the squeamish may begin to wonder if they ought to retreat to some slower-paced treatment of the subject. Do not give up at this point; hang on until you have seen transistors, at least. One of the most striking qualities of this book is its cheerful evasion of complexity whenever a simpler account can carry you to a good design. The treatment of transistors offers a good example, and you ought to stay with the course long enough to see that: the transistor chapter is difficult, but wonderfully simpler than most other treatments of the subject. You will begin designing useful transistor circuits on your first day with the subject.

It is also in the first three labs that you will get used to the lab instruments – and especially to the most important of these, the oscilloscope. It is a complex machine; only practice will teach you to use it well. Do not make the common mistake of thinking that the person next to you who is turning knobs so confidently, flipping switches and adjusting trigger level – all on the first or second day of the course – is smarter than you are. No, that person has done it before. In two weeks, you too will be making the scope do your bidding – assuming that you don't leave the work to that person next to you, who knew it all from the start.

The images on the scope screen make silent and invisible events visible, though strangely abstracted as well; these scope traces will become your mental images of what happens in your circuits. The scope will serve as a time microscope that will let you see events that last a handful of nanoseconds:

the length of time light takes to get from you to the person sitting a little way down the lab bench. You may even find yourself reacting emotionally to shapes on the screen, feeling good when you see a smooth, handsome sinewave, disturbed when you see the peaks of the sine clipped, or its shape warped; annoyed when fuzz grows on your waveforms.

Anticipating some of these experiences, and to get you in the mood to enjoy the coming weeks in which small events will paint their self-portraits on your screen, we offer you a view of some scope traces that never quite occurred, and that nevertheless seem just about right: just what a scope would show if it could. This drawing was posted on my door for years, and students who happened by would pause, peer, hesitate – evidently working a bit to put a mental frame around these not-quite-possible pictures. Sometimes a person would ask if these are scope traces. They are not, of course; the leap beyond what a scope can show was the artist's: Saul Steinberg's. Graciously, he has allowed us to show his drawing here. We hope you enjoy it. Perhaps it will help you to look on your less exotic scope displays with a little of the respect and wonder with which we have to look on the traces below.



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