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Thomas C. Hayes and Paul Horowitz
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Student Manual
for
The Art of Electronics

Thomas C. Hayes
Paul Horowitz

Harvard University



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TO TURNER, TESSA AND DEBBIE; TO MISHA, JACOB AND CAROL

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-

PREFACE

This manual is intended to be used along with *The Art of Electronics* by Horowitz and Hill (Cambridge University Press, New York, 2d ed. 1989) in an introductory electronics course. The manual includes three principal elements:

- laboratory exercises: 23 of these, each meant to occupy a 3-hour lab period; each set of laboratory notes except the last includes a reading assignment in the Text;
- explanatory notes: one for each laboratory exercise or class;
- worked examples: a total of 20: approximately one for each reading assignment.

In addition, we have included some reference materials:

- a glossary of frequently-used terms and jargon;
- review notes for each chapter, noting the most important circuits and topics;
- selected data sheets, analog and digital.

The students this course might suit

These notes arose out of a course at Harvard; they define what we try to teach in that busy term. The course does less than all of Horowitz and Hill, of course. We treat chapters 1-11, omitting Chapter 7, on *Precision Circuits...*, which is more specialized than the rest, and skimming Chapter 4 on *Active Filters and Oscillators*. Even this selection includes more information than we expect students to absorb fully on a first pass through the book. This Manual tries to guide students to the most important material.

The *typical* student that we see—if there really is a typical student—is an undergraduate majoring in Physics, and wanting to learn enough electronics to let him or her do useful work in a laboratory. But we do not assume such background in these notes. Students very different from that typical student thrive in our course. Graduate students in the sciences appear regularly; during the summer we see many high school students, and some of these do brilliantly; now and then a professor of Physics takes the course (and they do all right, too!). In the ‘extension’ version of the course, we see lots of programmers who want to know what’s going on in their machines, and we see people who just happen to be curious about electronics. That curiosity, in fact, is the only prerequisite for this course, and suggests the only good rule to define who will enjoy it. Someone looking for an engineering course will find our treatment oddly informal, but a person eager to learn how to design useful circuits will like this course.

Laboratory Exercises

The laboratory exercises build upon a set of labs that were set out in the 1981 edition of the *Laboratory Manual*, by Horowitz and Robinson. The new exercises replace all of the original digital labs and substantially revise the analog labs on FET’s and oscillators. In the digital section we have switched over from LSTTL to HCMOS, but the major change has been the enlarged role given to the microprocessor labs, and the shift from the Z80 processor programmed rather laboriously via a DIP switch to a 68008 processor programmed through a keypad. (A complete schematic is included. See Lab 15. Complete keypad units are available through the authors. See Parts list).

We have held to our intention that students should build their computer from the chip level, and that they should not be handed a ROM cleverly programmed by someone else.

We want our students to feel that they know their computer intimately, and that it is fully *their* product.

The digital half of the course now centers on the microcomputer: we meet simpler digital devices—gates, flip-flops, counters, memory—partly because we want to be able to build small digital circuits, but also partly in order to understand the full microcomputer circuit. To put this point another way, the final series of labs, in which the microcomputer gradually takes form, draws together every one of the several circuit elements met earlier: combinational logic networks, flip-flop circuits, counters, memory, and analog/digital conversion. The A-D conversion experiments have been expanded to include the effects of sampling-rate and of filters applied to input and output.

Notes

The notes that introduce each lab respond to two needs that students often voice:

- The notes *select* a few points from the much broader coverage of the Text; those selected points are, of course, those that we think most important to a student meeting practical electronics for the first time.
- The notes *explain* at length. They do this at a level more basic than the Text's, and they provide explanations in a step-by-step style that the Text cannot afford, given its need to cover far more material.

A suggestion: how to use the notes

Here's a proposal; you will, of course, find your own way to use Text, Notes and all the other course materials. But here is one way to begin.

- Start by reading the day's assignment in the Text. It will include some material that is subtler than what we expect you to pick up in a first course. You may want to hear some points restated in another way, or you may want to see an example worked. Primed with this specific sort of curiosity, you might then—
- Look at the day's Notes and Lab: scan, first, to see which circuits and which points are selected. Read the Notes on any points that puzzled you; if you still are puzzled, return to the Text for a second look at the topics you now know are most important.
- *Skip* topics in the Notes that you understand already. The Notes are meant to help you, *not* to burden you with additional reading: if you have read and understood the Text's discussion of a topic, you will miss nothing by omitting the corresponding section in the Notes.
- Try the day's worked example, at least in your head. If it looks easy, you may want to skip it. If it looks hard, probably you should try to do your own solution. If you find yourself heading into a lot of work—especially any involved calculations—probably you are doing unnecessary labor, and it is time to peek at our solution. We hope to teach you an approach to problems of circuit design, not just a set of particular rules. If there is a laborious way and a quick way to reach a good design, we want to push you firmly toward the quick way.

We expect that some of these notes will strike you as babyish, some as excessively dense: your reaction naturally reflects the uneven experience you have had with the topics the Text and Manual 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 Manual grew—and, earlier, the Text as well—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 the Text and this Manual will help to make those exercises instructive.

Why our figures and text look the way they do

You will discover very quickly that this manual is informal in language and layout. The figures all are hand-drawn. They are done by hand partly because we like the *look* of hand-drawn figures (when they are done right; not all our figures are pretty), and partly because we want to encourage students to do their own free-hand drafting of schematics. In some cases we did *draft* drawings on a computer, then drew the final versions by hand! The text was produced as camera-ready copy, put out by an ordinary PC word processor. So—as writers used to say, long ago—dear reader, look with sympathy, if you can, when you find a typo, or a figure drawn amiss. Don't blame the publisher for corporate sloth. Picture, instead, two fellows hunched over their keyboard and drawing board, late at night and beginning to get drowsy.

Who helped especially with this book

Two teaching fellows gave us good advice on uncounted occasions: Shahn Majid, a mathematical Physicist who taught with us for years in the Harvard College course, and Steve Morss, a digital engineer who once took the course and then returned to teach. Steve often would linger late into the night helping to try out a new circuit or analyze an old one. Both of these two could perfectly well have taught the course, and chose nevertheless to linger—Bodhissattva-like—giving their expert help in this quieter way.

A pair of our former students, Jeff Hobson and Wei-Jing Zhu, helped us first by drawing figures—and then gradually turned into this book's godparents, helping in all sorts of ways. Often they would arrive in the evening, at the end of a long day's work, and then would labor to help us organize, check, re-check—and also to make judgments on how to make our points clearly. Often the end of the workday was defined by the departure of the last bus, at 1:00 in the morning. Their devotion to the project was invaluable, and touching.

Finally, Debbie Mills deserves thanks for putting up with her husband Tom's strange, long hours, and then, toward the end, doing much more: providing essential help in organizing, checking, and correcting the growing stacks of printouts and drawings.

*Tom Hayes
Paul Horowitz*

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