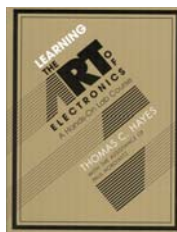# Learning the Art of Electronics

A Hands-On Lab Course

Thomas C. Hayes

Cambridge U. Press, 2016. $79.99 paper (1150 pp.). ISBN 978-0-521-17723-8

The third edition of the widely used guide to electronic circuit design, *The Art of Electronics* (Cambridge University Press), hit bookshelves in 2015. Now its companion volume, previously the *Student Manual for the Art of Electronics* (Cambridge University Press, 1989), has doubled in size and scope. Author Thomas Hayes, who has taught laboratory electronics at Harvard University for more than two decades, designed the new volume for a full-semester laboratory course. *Learning the Art of Electronics: A Hands-On Lab Course* is organized into 26 chapters, each offering rich context and clear explanations in labs, notes, supplementary material, and worked problems. A close overview of the book's contents will give instructors the best sense of whether the $80 investment will pay off for their courses.

The book's labs are balanced between analog and digital electronics. Hayes begins with familiar analog circuitry and includes discussions of voltage dividers, Ohm's and Kirchhoff's laws, and Thevenin equivalents. The labs tackle *RC* filters in both time and frequency domains with a cheerful approach that is not overly mathematical, although as a physicist, I would have liked a more nuanced description of why voltage signals appear to "pass through" a capacitor. By lab 3, students use their *RC* filters to build an AM radio receiver.

The book moves on to cover bipolar transistors at increasing levels of complexity. Students build a discrete operational amplifier, or op-amp, the fundamental building block of analog electronics. The sequence features some of the book's best labs; students who complete them will no longer take for granted the integrated circuit op-amps that have been widely available for 50 years.

After explaining how to build an op-amp, *Learning the Art of Electronics* devotes four labs to using them. In one particularly well-designed lab, students amplify and integrate the signal generated by twisting the shaft of a servo motor, producing an output signal that corresponds to the angular position of the shaft. The final op-amp lab instructs students on how to make an active filter and a power booster, effectively illustrating the challenges of op-amp stability.

In lab 10, students build a proportional-integral-derivative controller to regulate the position of a DC motor. Voltage regulators, both linear and switching, are constructed in lab 11; lab 12 introduces analog switches. Two types of oscillators are covered: the venerable 555 relaxation oscillator and the lamp-stabilized Wien bridge. In lab 13, students use the 555 to modulate FM audio transmission. Two labs cover digital logic. New in Hayes's update is an introduction to programmable array logic, or PAL, and its Verilog compiler, used in lab 16 to create a 16-bit counter. (Verilog is a computer language for describing digital logic circuits.)

The last quarter of the course proceeds along parallel microcontroller paths. Instructors can choose between path 1, in which students use an 8051 microcontroller to build a microcomputer—a "big-board computer" complete with external memory and address bus—or the shorter path 2, in which they use a standalone 8051 microcontroller and develop code on an external computer. Hayes makes a strong pedagogical case for the first approach, which is similar to the way he had students build an op-amp before using commercial integrated circuit op-amps. Yet he acknowledges that path 2 "is the way everyone else in the world works with microcontrollers."

Students on the microcomputer path begin with lab 16 and its 16-bit counter, which serves as an address counter for Hayes's big-board computer. The next couple of labs cover, among other things, analog-to-digital converters and state machines, useful for sequenced operations such as serial communication protocols. Lab 19 offers a choice among four digital projects.

Over the next five labs, students assemble (path 1) and program (either path 1 or 2) the microcomputer or microcontroller with the help of code examples in
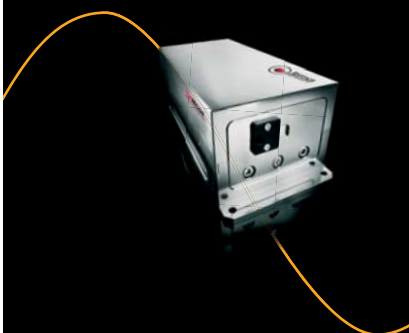
assembler and C languages. The book concludes with a gallery of games and other creative student final projects. Appendices cover analog and digital oscilloscope usage, a Verilog primer, and notes on transmission lines.

With more than 1100 pages, *Learning the Art of Electronics* is a massive and ambitious text. In any undertaking so large, typos abound, but an active errata website is gathering corrections for subsequent printings. The book retains many of the handsomely drawn circuits of the original *The Art of Electronics* and is much more comprehensive. However, some attention-getting analogies—for example, figure 4N.12, which describes a "rose colored lens" in terms of a stout girl and a scrawny boy—set the wrong tone and should have been retired in 1989. The editors, I suspect, know this; both the caption and a footnote invite the reader to interchange genders, and yet the humor relies on body shaming either way.

Instructors will want to know if *Learning the Art of Electronics* can stand alone as an undergraduate lab text. The answer is yes. While the book does cross-reference *The Art of Electronics*, it "means to be self-sufficient," and it achieves that goal. I would lean toward path 2 for the microcontroller labs, given the low-cost, high-pin-count microcontrollers and compilers that can be readily substituted to streamline final projects. In no way, however, should that recommendation be considered a criticism of Hayes's fine introduction to electronics.

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