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ANALOG DESIGN: THE ACADEMIC VIEW

Analog design needs a change in perspective

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Analog design has long been overshadowed by digital design. Nevertheless the "real world," at least at the macro level, is analog rather than digital, and most electronic systems ultimately have to interface at both input and output with the analog world.

Correspondingly, electronics students tend to think that analog design is more difficult than digital design because of the perception that analog problems are ill-defined and there is no unique answer. Indeed, analog designers commonly find themselves well-educated when they graduate but ill-equipped to handle the problems with which they are immediately faced in industry.

Whether you are an analog-design engineer, supervisor or manager, you can significantly increase your productivity and value to your company, as well as gain the satisfaction of mastery over methods, by use of design-oriented analysis to obtain low-entropy expressions.

Over many years of teaching courses for audiences ranging from undergraduate students to experienced industrial engineers, I have discovered that there are many ways to help graduates accomplish the transition from student to engineer more effectively and efficiently. This process can be initiated by college teachers, and supported and augmented by engineering managers and supervisors.

The starting point is a change of perspective. Yes, analog-design problems are ill-defined in the sense that there are never enough equations to solve for the number of unknowns. In fact, not nearly enough, in the mathematician's sense. Still, as engineers, we have to solve the problem anyway. So, the usual negative approach instilled in us at an early age of: "I don't have enough information, so I can't solve the problem," must be replaced by the positive approach of: "Somehow or other I have to find additional information to make the necessary trade-offs and approximations so I can do the design."

I want to expand on the following positive approach, expressed in terms of some new names:

- *design is the reverse of analysis*, so only *design-oriented analysis* is of any value.
- The result of design-oriented analysis is a *low-entropy expression*, from which more useful design information can be obtained than simply one numerical answer for an assumed set of component values.

Let's start with an examination of the familiar path facing a new graduate. Scenario: The graduating engineer falls off a cliff.

Typically, an electronics engineer graduates with his mind filled up with formal analysis methods, theorems and derivations. He is well-skilled in solving simplified, sanitized analysis exercises that have unique answers: one answer is correct, all others wrong. The system is this way for good reasons, namely that most such exercises are graded by teaching assistants who have neither the time nor the experience to evaluate an answer that doesn't fit the one provided by the instructor.

In any case, when the new graduate engineer starts work, he is soon faced with a new situation, perhaps to prepare a response to an RFP (request for proposal). If this happened to you, probably you leafed through a thick document and eventually found a couple of pages worth of technical specifications. Upon absorbing this meager information, were you, like so many others, hit with the depressing realization that you had no idea where to start?

After a period of thrashing about, you may have sought the help of a colleague, who perhaps provided a blueprint for a previous similar design. With renewed optimism, you now had a circuit to work on and proceeded to write down all the equations you could think of. After two or three pages of rapidly expanding algebra, depression probably again set in as you realized that the algebra had become unmanageable and wouldn't lead to anything useful anyway.

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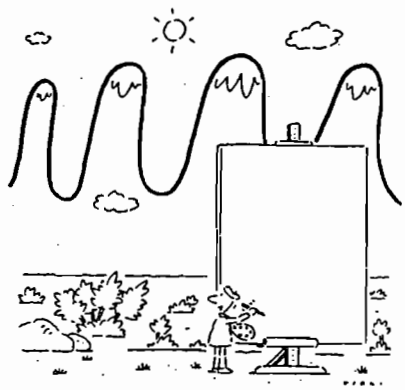
After another period of thrashing about, which likely included a feeling of helplessness and chagrin that nothing you had learned seemed to be of any use, you probably took yet another tack: you got your technician to breadboard the previous similar design so you could get a solid starting point. When the breadboard was fired up, you may have become distressed by a new realization: Your technician knew a lot more than you did, especially about how to debug.

Now began the final, and longest, phase of the new engineer's adjustment to the real world. You learned how design is "really" done: by a combination of cut-and-try, knob-twiddling and guesswork. In time, these techniques grew and multiplied into competence and intuition, and you eventually developed into an experienced design engineer.



The above scenario, of course, is oversimplified and exaggerated in order to make two points. First, *design* is the reverse of *analysis*: one starts with the answer, which is the specification, and one has to work back to what circuit configuration to begin with and what component values to use.

Second, what one is taught is mostly analysis, so there is a wrenching transition to the real world, like falling off a cliff. The engineer restarts his learning process from the empirical approach, while most of his academic knowledge, after his first abortive attempt to apply it, rusts away in his mind and is forgotten.

This situation is wasteful and inefficient, besides being unfair to the engineer. Despite well-advised and well-meaning efforts to increase the amount of "design" in engineering curricula, design remains an application problem following, and separate from, conventional analysis. I believe design can be integrated into analysis at a much more fundamental and detailed level.

"Design" is a process that follows a sequence of steps. One starts with a simple, approximate model, perhaps a block diagram, and some basic quantitative relationships that establish the required functions and number of stages. One then gradually augments the model with more detail, progressing toward the right as the accuracy/simplicity trade-off shifts toward greater accuracy and less simplicity. Iterations are necessary when a tentative choice has to be changed, or when simulations or experimental measurements do not agree with predictions.

Time and cost are important ingredients in the trade-offs, especially in determining the termination point. An efficient design process requires a smooth and gradual progress. It is especially important not to resort to the computer too soon, and to resist the tendency to expect the computer to do your thinking for you by giving it the whole problem to solve at once. The computer can actually introduce additional iterations, unless the user is thoroughly familiar with the algorithms embodied in the software.

Each design iteration loop can be considered as a local feedback process. The analysis result is compared with the specification, which is the desired answer, and discrepancies are to be corrected by modifying the model and/or changing numerical values. To do this, the analysis must be worked backward or interpreted in terms of the contributions from the original circuit elements.

Working the iteration feedback loop is the essence of the design process, and is facilitated if the initial result is obtained by design-oriented analysis, which is simply a name to emphasize that analysis must be usable "backwards" for design, and any analysis that cannot be thus used is a waste of time.

Well, what is design-oriented analysis? It is the process of controlling and guiding the algebra so that the result is a low-entropy expression, defined as one in which terms are ordered, or grouped, so that additional insight is obtained into the relative importance of the various contributions to the result. This is the source of the additional information needed for design, and substitutes for the missing equations that would be needed to solve formally for the number of unknowns.

The word "entropy" is borrowed from physics, and defined here only qualitatively, as above. In contrast, a high-entropy expression is one obtained by "blind" application of algebraic manipulations, usually leading to sums of products of circuit elements, and gives no insight into how the relative values affect the result.

Lowering entropy requires input of en-

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What *is* analog design?

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ergy; in this case, it takes mental energy to direct algebraic manipulation to derive the low-entropy result from the high-entropy one. It would be much more efficient, and easier, if one could derive the low-entropy result directly, without letting the entropy rise in the first place. This is where the various methods of design-oriented analysis come in, one of which is use of Thevenin's and Norton's theorems.

Still useful

These theorems taught in school are useful in that every time you use Thevenin's or Norton's theorem, you get rid of one loop or one node of the circuit. Therefore, by successive use of the theorems, you can reduce a complicated circuit to a single loop and write the result by inspection. And, there's a bonus: Not only do you get the result with less algebra, but the result also is automatically in low-entropy form, because the elements automatically get grouped during the reduction process.

There are many more sophisticated techniques (read: tricks, shortcuts) for using design-oriented analysis to obtain low-entropy expressions that are useful for design. It's just a matter of practice—and motivation. Performing design-oriented analysis to produce low-entropy expressions does not require learning new principles or theorems. If anything, it requires unlearning some things that have been deeply ingrained from an early age, such as: If you don't have as many equations as unknowns, you can't solve the problem—and that you shouldn't make an approximation if you can't justify it.

On the contrary, a design engineer has to solve the problem with insufficient equations, and one of the ways to do it is to make all the approximations you can, justified or not, leave behind a wake of assumptions and approximations, so at least you get an answer—which is better than no answer at all. Of course, you have to go back and check them out. The best that can happen is that the approximations are OK, in which case you're home free; the worst that can happen is you have to go back and reject some of the approximations. Regardless, you can't lose by trying—even a failed approximation usually suggests an alternative.

What design-oriented analysis does need is development of a different perspective on the goal of analysis: You control the algebra, rather than let it control you. Make the answer come out in low-entropy form.

Uncertain principles

One might say that we all have to go through a process of "technical therapy," a sort of Freudian regression in which we have to unlearn some of the earliest things we were taught so that we can make a new start in which algebra is viewed as our servant, not our master; and that approximations are valuable, even essential, in getting an answer, not something to be fearfully conceded in a rearguard action against overwhelming algebra.

In general, "technical mental health" is achieved when we adopt the overall positive viewpoint that the problem can indeed be solved with the proper approximations and assumptions. We, as academics, can respond to the challenge to reorient our teaching so that our engineering students are better prepared to survive the transition to design engineer, thus giving them a chance to benefit from their formal background.

Supervisors and managers, who may or may not have had design experience, can also benefit from encouraging their design engineers to develop low-entropy results. Typically, reports and design reviews are presented with results in high-entropy form, analytic expressions that give no information other than that obtained by substitution of a set of element values. The design engineer says something like, "It seems to be working, at least over part of the range."

You, as a supervisor or manager, often can only say, "Well, looks as though it's coming along all right, carry on." In contrast, if you insist that results be presented in low-entropy form, you not only ensure that your design engineer has better insight into and control over the design, but you yourself can interpret the results and offer suggestions and guidance.

SOURCE CODE

By Ray Weiss

An analog hero

I've spent a career dodging analog electronics. It started in school when I ran into the underlying indeterminism that characterizes the analog world. In analog, you do a preliminary circuit, get your equations together, and start "guesstimating" the component values. I headed for more deterministic disciplines, such as high-level mathematics, hardware logic/systems design and programming. These avoided the underlying real world which, at best, is messy. And lots of others did the same. So, now there's an analog designer shortage.

Over time, I became adept at evading analog—even as clock rates ominously rose, and digital signals increasingly resembled RF reflections. That ended a month ago, when I ran into R.D. Middlebrook, an eminent Caltech professor and analog researcher. A soft-spoken, transplanted Briton, Dr. Middlebrook is a polite-but-passionate analog zealot. And he is out to make analog design easy to learn and do.

He's also persuasive. So persuasive that I found myself—me, a digital and software guy—actually sitting in on an analog design class for industry. Even more surprising, I understood it! For the first time, I could get to solutions without developing a hernia from heavy algebraic lifting.

And it wasn't just me. One of the top power-supply consultants in the country also was there. "I use a lot of these techniques already," he said. "And some of these I've never heard of, but I'm going to be using them. They really simplify design."

A number of the engineers at the class are ex-Middlebrook acolytes who came back for recharging. One, Mark Fortunato, now at Citicorp/TTI (Santa Monica, Calif.), said, "I use his techniques all the time. I'm back because I couldn't read all my old notes and there are even more techniques now."

The class was a real eye-opener. Here's a peek at some of Middlebrook's magic shortcuts, tricks and techniques for how to:

- Build low-entropy (simplified, low-complexity) equations for easy design solution.
- Use an iterative design process or methodology—starting from initial analysis cuts to a final design—minimizing algebraic manipulation and maximizing design choices.
- Solve quadratics without square roots—simple approximations to reduce hard-to-work-with equations.
- Reduce complex linear circuits to easily analyzable forms using Thevenin's and Norton's theorems, and how to do algebra on the circuits, instead of working with large, cumbersome equations.
- Draw/find circuit poles and zeros without heavy algebraic lifting, using inverted poles and zeros, and neat estimation techniques on log/log drawings (db or phase vs. freq).
- Add an additional component to a circuit for analysis without having to start over (Additional Element Theorem).
- Find loop gain by injecting a test signal into a closed loop instead of breaking loop feedback path and calculating A and K separately (Feedback Theorem).
- Find I/O impedances from circuit gain by taking simple limits, reducing to one equation (I/O Impedance Theorem).

If you're an analog designer and aren't using these shortcuts, you're working way too hard. There's a better way. Middlebrook calls it "design-oriented analysis." As he puts it: "Most analog design works backward from a solution. Unlike school problems, you typically know the answer—what you need is a design. The object is to do design. So, set up analysis criteria that make it easy to write and analyze equations. Reduce equations so you can easily see the relative importance of elements, as well as select key values."

It's a streamlined way to do analog design, eliminating equational overload. By simplifying circuits, by making viable approximations and by using easy representations, equations reduce to intuitive forms; you can see the circuit and select values.

Unfortunately, analog design isn't going away; in fact, it's going critical, as clock rates climb. Like it or not, we will have to deal with analog beast. And so I'd like to offer a toast to Dr. R.D. Middlebrook—he's making analog easy.