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A Different First Course in Electrical Engineering

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Introductory courses have changed in many schools, but our informal survey revealed that many stress *how* to present concepts rather than addressing *what* concepts should be taught. Most studies of the curriculum focus on the ordering of material rather than concentrating on what should be taught [1], [2]. For example, the signal processing community has shown the benefit of teaching digital signal processing as the first exposure to electrical engineering concepts [4], [5]. This tack amounts to showing that linear signal and system theory provides a good springboard, with *digital* signal processing allowing the student to experiment using tools such as Matlab. In contrast, we wondered if we were teaching the right material. We were not interested in debating whether analog or discrete-time analysis should be taught first, and did not question the value of linear signals and systems analysis. All electrical engineering curricula have infused more computer engineering into courses while tossing out material deemed less relevant. At Rice, this process has occurred over several years, resulting in an evolutionary approach with isolated issues (like "What goes into this course?") as the focus rather than broad curricular goals. More pointedly, could there be a framework for structuring what material to teach electrical and computer engineering undergraduates, and for teaching that material?

To paraphrase thoughts presented by Dr. Andrew Viterbi during his Brice Lecture given at Rice in 1996, the long-standing model for electrical engineering education was *that the fundamental technology(s) needed by undergraduates should be taught early and often*. Certainly before 1950, one key technology sufficed: circuit theory. Virtually all electrical engineering designs were realized and/or modeled with analog circuits. This single technology served all the main areas of electrical engineering: communications, electromagnetics, and power systems. In the middle of the 20th century, three events occurred in an 18-month period that ushered in huge changes in electrical engineering. These events were the demonstration of the electronic digital computer (1946), invention of the transistor (1947-8), and the publication of Shannon's information theory (1948). Somewhat later (in the early 1960s), the laser was invented, and further enhanced the technologies that were available. Since the middle of the century, these fundamental research results have been refined and elaborated, and have become technologies that, along with analog circuits, comprise implementation choices for design. Due to this explosion of technology and theory, the electrical *and* computer engineer can realize designs in a variety of ways. The choices are many: where should analog and digital realizations be used, where should hardware and software be used, and how should systems interface with computer networks?

Clearly, no single core subject can be identified for today's engineer; the bachelor's level engineer needs to understand design alternatives rather than focus on one implementation mode. In fact, technological developments seem to be occurring at an increasingly rapid pace, which has had the effect of rendering some design choices obsolete. No longer do component-based designs dominate; instead, design revolves around off-the-shelf chips or custom integrated circuits. Software has become increasingly important, which has enabled the algorithm to be an important engineering consideration. What new important algorithms or technologies will emerge in the next 10 years is purely guesswork, with university faculty no more or less able to predict the future than people in industry.

Engineering programs strive to prepare their students to cope with change and adapt to it. To our way of thinking, no single technology (like circuits, be they analog or digital) nor approach (linear system theory taught either from analog or digital viewpoints) captures modern electrical and computer engineering. Today, hardware vs. software, analog vs. digital, optical vs. electrical, packet-switched vs. circuit-switched, are among the crucial decisions engineers must make. Thus, the latter half of this century differs from the first not only in technology, but also in engineering approach. *A single pre-eminent technology no longer exists*. A curriculum must explore technology, providing students with the short-term knowledge of what technologies are available, and with the long-term experience of how technology affects design decisions. We know what the technologies are; how does one chart the curricular map with so many choices? Faced with this issue, we decided a curriculum should rest on why technologies are being used: What has motivated inventions and what drives engineering applications? Our conclusion is that *information* underlies most of modern electrical and computer engineering,

Table 1. Fundamentals of Electrical Engineering I.*

- Introduction to signals and systems. Fundamental model of communication.
- Representing information as voltages and currents. Circuit element voltage-current relations in time and frequency (impedance) domains. Transfer functions and the notion of filtering, with implementation by operational amplifiers.
- Representing information with analog signals.
  - Frequency-domain analysis of signals: Fourier series, Fourier transforms, Parseval's Theorem and spectrograms. Fundamental model of speech.
  - Analog communication: amplitude modulation transmitted through additive white noise channels. Signal-to-noise ratio.
- Digital representation of information
  - Digital signal analysis: sampling theorem, A/D conversion, difference equations, DTFT, DFT and FFT. Analog and digital alternatives to filtering.
  - Digital communication: source coding theorem, Huffman codes, compression (lossless and lossy) and matched filter receivers. Channel capacity, the noisy-channel coding theorem and error-correcting codes.
  - Ethernet as an example computer network. Introduction to protocols and the Internet.
- Comparison of analog and digital (PCM) communication.

*Syllabus for our first course in electrical and computer engineering. For more detail, the course's web page can be found at http://www.owlnet.rice.edu/~elec241.

from semiconductor devices to computer networks and protocols. (Power systems are one exception to the broad theme of information.)

This section describes the introductory course we developed at Rice for electrical and computer engineering majors. The course addresses how information is represented, manipulated, controlled, and communicated by electrical means. It is a "top-down" course that stresses broad considerations in analyzing and designing information systems.

Course Design

To set the context for developing our course, a little background. Rice University has a relatively small engineering school. Out of a total undergraduate population of about 2,500, roughly 30% are engineering students. The Electrical and Computer Engineering Department is the largest in the engineering school, graduating over 50 bachelor's students each year. Our engineering graduates are well recruited, both by industry and graduate schools. The educational mission of Rice's engineering program, which crystallized recently as part of the engineering school's strategic planning process, is to educate technological leaders through course work and interdisciplinary projects that stress fundamentals and what we term the *engineering context*: the milieu within which engineers must practice.

At Rice, we continued to use circuit theory as the first electrical engineering course even as the department changed its name to Electrical and Computer Engineering over 15 years ago. Since Rice's opening in 1912 until we decided to change it, our introductory electrical engineering course was circuit theory, normally taken in the sophomore year. Early in 1997, we decided to implement our idea of a *breadth-first* introductory course focused on information science and engineering. Classic circuit-theory-oriented, or even DSP-oriented, courses tend to be "bottom-up" courses. They stress fundamentals without providing much of the context that drives their importance. We preferred the "top-down" approach that starts with a large problem and addresses approaches to solving it. "Large" was chosen here because some introductory courses begin by taking apart (literally and conceptually) a technology like the compact disk and use it to motivate engineering concepts. Our big problem is information: What are the tradeoffs to various alternatives of information system design?

In designing the course, we wanted to include both digital and analog approaches, with the importance of new devices brought forward as examples of what the students (not the instructor) will face as design alternatives. We quickly found that our room to expand breadth was constrained by the need to provide prerequisite basics for succeeding courses. While we wanted the new course to instill an appreciation for the big picture, we still needed to implant basic knowledge and skills. Although we could eliminate or postpone much of the circuit theory we had been teaching, considering the basics we needed to keep and the breadth we wanted to add meant that we were looking at a very "dense" course. The obvious solution was to add a second semester. We are changing the second-semester course more than the first; this section concentrates on the more stable first-semester course. We gave the courses the unexciting, but symbolically important, titles "Fundamentals of Electrical Engineering I & II."

The course description for the first course is shown in Table 1.

Course Structure

Listing course topics does not accurately portray how the course operates. We focus from the beginning not on technique but on *goals*: What is the engineer trying to do and what are some alternatives to problem solution. Our intent is not to develop a complete framework for evaluating technologies within the course, but to inspire students; to introduce a systems-level, top-down design approach; and to start them thinking about what their

Table 2. Example Homework Problems.

1. Digital Filtering of Analog Signals

RU Electronics wants to develop a filter that would be used in analog applications, but is implemented digitally. The filter is to operate on signals that have a 10-kHz bandwidth, and will serve as a low-pass filter.

(a) What is the block diagram for your filter? Explicitly denote which components are analog, which are digital, and which interface between analog and digital worlds.

(b) What sampling rate must be used and how many bits must be used in the A/D converter for the acquired signal's signal-to-noise ratio to be at least 60 dB?

2. Mixed Analog and Digital Transmission

A signal is transmitted using amplitude modulation in the usual way. The signal has bandwidth W Hz, and the carrier frequency is f_c. In addition to sending this analog signal, the transmitter also wants to send ASCII text in an auxiliary band that lies slightly above the analog transmission band. Using an 8-bit representation of the characters and a simple baseband BPSK signal set (the constant signal +1 corresponds to a 1, the signal -1 to a 0), the data signal representing the text is transmitted at the same time as the analog signal.

(a) What is the maximum datarate the scheme can provide in terms of the bandwidth W_x available for transmission?

(b) Find a receiver that yields both the analog signal and the bit stream.

technological contributions might be. The design process itself is not emphasized until succeeding courses. We felt that to cover information technology broadly meant that they would be ill-prepared to perform well in realistic design situations. In the first course, we stress alternatives from a broad view, as would occur in the beginning stages of understanding the issues from a top-down design viewpoint. Open-ended situations occur throughout in the form of problem sets that are not drill-oriented. Table 2 shows some homework examples. We also emphasize working in groups, both on problem sets and in the laboratory. In summary, we try to set the stage for succeeding courses so that students implicitly know the application of advanced material presented in upper-level courses.

In the laboratory portion of the course, we revamped not just the context, but also the style. Previously, the lab was a somewhat regimented experience. Students would arrive at the beginning of the scheduled session, check out a set of equipment (scope, function generator, multimeter, power supply, and breadboard), and carry it to a bench. Parts were drawn as needed from a set of cabinets containing standard components. At the end of the session, circuits would be disassembled and parts and equipment returned to the storeroom. Our first change was to permanently set up the equipment on the benches to reduce setup overhead and allow flexibility in access to laboratory facilities. This change meant that several courses would use the same equipment. We gave each lab group (two students) their own breadboard and a kit of electric and electronic parts, including components required for course laboratories and additional components for adjustments and experimentation. In addition, each student is given a set of basic tools that are useful in both this and all succeeding hardware courses. Armed with tools and parts, students are encouraged to work outside of laboratory hours on any project they wish, using laboratory equipment if they wish.

In addition to the analog instruments at each lab station, we added PCs running a browser, LabView from National Instruments, and Matlab. This addition significantly improved both the capabilities and the efficiency of the lab. The lab manual is kept online as a web document, *http://www.ece.rice.edu/\~jdw/241/241.html*, (profusely illustrated in the early labs in which students are introduced to components and instrumentation). Reference data such as the color code and component data sheets are also available. We use LabView both for building "virtual instruments" (spectrum analyzer, true RMS voltmeter, frequency response measurement, distortion analyzer) and for performing real-time digital signal processing (filtering, quantization, control law implementation). Using this equipment and software, looking at a signal's spectrum is just as easy as looking at its waveform. Matlab is used for more involved, "batch" signal processing, such as filter design and spectrogram display. Students are not asked to program in either environment, and use LabView as another instrument and Matlab for its computational power. (We have found programming, especially in the early undergraduate years, to be a time-consuming process. Students simply lack needed experience, and the course places enough demands on their time as it stands.) Signals are a main theme, and the lab seeks to reinforce this by instilling a natural, intuitive feeling for signals as real objects rather than simply an abstract concept. It does this by concentrating on signals that can be heard. The very first lab introduces students to "the sound of signals." Subsequent labs continue to use the students' ears (and mouths) as part of the instrument suite. Concepts such as spectrum, frequency response, distortion, quantization, and aliasing are all illustrated aurally as well as visually. The standard speech model is taught and used to interpret speech spectrograms.

The capstone laboratory is a full-duplex optical (free space) telephone system. Each lab group constructs and tests their system individually, then must demonstrate it by communicating with another group across the length of the lab. Parameters are chosen so that the signal-to-noise ratio for the base system is marginal, and students are given suggestions for improvements.

We also use what we call, for lack of a better term, *recursive teaching*. We introduce a concept superficially at first, then come back to it over and over, each time with more sophistication and insight. Good examples of this approach are communication (the block diagram of the fundamental model is presented the first day), the complex exponential (again exhibited the first day as an example signal and re-explored with each new variant of the Fourier transform), and filtering (first arising as an interpretation of circuit-based transfer functions, then later as ideal filters for sampling and noise reduction). We find that students are initially uneasy with what they readily perceive to be a superficial grasp of the topic. We assure them that we will return to the topic, and once we do, it is our (admittedly subjective) perception that the students are grasping (albeit sometimes tenuously) many of the "advanced" concepts being presented to them. One area where we can definitely claim success in stimulating the students is the lab. Several students have remarked that "This lab is fun."

Conclusions

The two courses were first taught during the 1997-98 academic year, which means that evaluation is, at the time of this writing, preliminary. The most dominant comment is "this course is hard, but I learned a lot." Despite our course's difficulty, few students drop out (about 5% the last time it was taught), and most enjoy it. From our perspective, we have found that teaching the broad view is more difficult than saying we will. It is all too easy to be diverted into analyzing Fourier transform properties than it is to provide students with reasons for studying it in the first place. Each time we have taught the course, we have scaled back the detail, provided more examples, and increased the discussion of broader issues.

The biggest hurdle in this course has been the students' lack of what we term "mathematical sophistication." In general, students enter Rice with strong mathematical backgrounds in that they can perform isolated calculations correctly—differentiate and integrate functions, for example. However, when it comes to generalizations of techniques that they know well, uncertainty about "what to do next" quickly develops. For example, every student would know how to simplify

$$\frac{d}{dx}(f(x)+g(x)),$$

but if we ask for

$$\frac{d}{dt}\sum f_n(t),$$

students generally become uncomfortable. In addition, calculations and formulas involving complex numbers make them ill-at-ease. Anyone who has taught circuit theory knows that students often stumble when the problem demands complex arithmetic. Not only do we introduce impedance, but we also explore the frequency domain thoroughly (we continually stress that signals have both time-domain and frequency-domain definitions, and that these definitions must be consistent). As a consequence, students face a higher complex-number hurdle in our course. To mitigate this problem, our approach is to develop engineering and mathematical ideas in parallel, taking time to make sure the mathematical manipulations are grasped. Some topics, such as information theory, have not been previously taught to undergraduate students. We do not teach probability in this course, but do rely on the concept of an average. Interestingly, students come to the course with elementary probabilistic notions, and notions such as average power and entropy are relatively easy concepts to teach.

Students who emerge from this course have a good idea about what electrical engineers do. One unexpected side-effect of the course has been the students' enhanced interest and ability to perform research. We currently have underclassmen involved in research projects. Because students emerge from the course knowing about the frequency domain, elementary information theory, what digital and analog signal processing are, and what an algorithm is, the better students understand the nature of open problems and have the background to learn the new analysis techniques (such as wavelet transforms). One junior-level student's paper was accepted at ICASSP [3]. On curricular issues, Rice's ECE department recently voted to remove the junior-level transistor circuits course from the core curriculum (it will still be taught and can satisfy upper-level requirements) as part of the de-emphasis of discrete-element circuits as essential knowledge for electrical engineers.

Clearly, Rice's and many other school's electrical engineering curricula are changing much more dramatically than in the past. At Rice, these changes have well-defined goals and motivation, with repackaging (re-ordering what we currently teach or teaching it differently) a lower priority. Today, information broadly underlies what our graduates do when they eventually enter the job market. We feel they are well served by an early exposure to information and the broad view.

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Just DSP

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The tools of the electrical engineer—often elegant, always powerful—are the result of the cumulative effort and