ANALOG SIGNAL PROCESSING FIRST

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ABSTRACT

The Department of Electrical and Computer Engineering at the University of Illinois recently adopted new undergraduate curricula. The most radical change was the introduction of ECE 210, Analog Signal Processing, in place of both the sophomore-level circuit analysis course and the junior-level signals and systems course. The new course combines core material from these traditional courses, along with applications such as AM radio and a modest laboratory component, in a way that improves both the students' understanding and their motivation. The new course still serves well as the base of the required curriculum and as a prerequisite for subsequent courses, while realizing savings in the early curriculum and allowing more time for advanced signal processing and systems courses in future semesters.

1. BACKGROUND

Four years ago, the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign embarked on a major revision of its curricula in both electrical and computer engineering. Perhaps the most radical change was the elimination of both the traditional sophomore-level circuit analysis and the junior-level signals and systems courses, with much of the material incorporated into a new course on analog signal processing, ECE 210. This new course occupies the same slot in the curriculum as the old sophomore circuit analysis course. ECE 210 contains some circuits material and the analog part of the signals and systems course. Some material in the circuit analysis course has been moved to the junior-level electronics course and to a new introductory course in the power and energy systems area. The discrete-time topics from the junior-level signals and systems course have been moved into our course on digital signal processing (DSP). The DSP course and the electronics course have been placed on a list of five "semi-required" courses from which students must select at least three.

The following sections of this paper introduce the motivation for the new ECE 210 course and describe its content, including brief coverage of its associated laboratory component. We then explain why we feel it is important that students be exposed to analog signal processing before digital signal processing. After successfully piloting this course twice, we have now taught it to all ECE students (200 to 300 students per semester) for the past four semesters, with good results.

This paper is an update of [1]. Reports on preliminary versions of this course have appeared in [2] and [3].

2. MOTIVATION AND GOALS

For more than 30 years, electrical engineering curricula have provided coverage of fundamental "circuits" and "systems" material through a sophomore linear circuits course and a junior-level signals and systems course. The traditional linear circuits course (with freshman physics and differential equations as prerequisites) introduces key circuit analysis concepts such as node and loop analysis via KCL and KVL, dependent sources and equivalent circuits, differential equation analysis of circuits with reactive elements, phasor methods, Bode plots, and often additional material such as three-phase electrical power systems. The signals and systems course emphasizes abstract linear systems analysis via differential equations and their solution, impulse response, convolution, Laplace transform methods, the Fourier series and transform, and sometimes includes state-variable concepts. This course typically includes the analogous discrete-time linear system theory (difference equations, z-transform, etc.) as well. Together, these courses have played a central role in the traditional EE curriculum, serving as the required fundamental education for all EEs in these topics as well as the gateway to all advanced courses in circuits, signal processing, communications, control, and other "systems" specialties.

In spite of their centrality to the traditional EE curriculum, these courses have been criticized on several fronts. For example, Ron Rohrer has argued that signal processing may now play the central, unifying role in modern electrical engineering that basic linear circuits once did [4]. The great educational innovator Mac van Valkenburg argued forcefully that a "top-down" or "just-in-time" approach, emphasizing high-level systems concepts and applications first (rather than a "bottom-up" approach starting with basic building blocks such as linear circuits) is both more motivating and pedagogically sounder. One move in this direction at Illinois has been the introduction of a freshman EE course with a strong laboratory component [5]. These arguments suggest that the first core course should teach systems or signal processing.

Our personal experience in teaching the traditional curriculum also revealed major deficiencies. While most students believed that circuits was an important topic for EEs, the lack of any explicit application in the introductory circuits course was demotivating and sacrificed an opportunity to connect this material with other concepts. The signals-and-systems course was traditionally taught as an abstract, applied mathematics course. In the rush to include every detail of both analog and discrete-time linear system theory, the natural connection of this material to circuit analysis was muted, and any serious discussion of applications was almost entirely foregone. Even students who did well in the traditional signals and systems course reported afterward that they had little idea as to the relevance of the course material to electrical engineers! We believe that these weaknesses were not unique to the University of Illinois' versions of these courses, but are inherent in the traditional curriculum.

It is easy to draw up a quick list of more targeted weaknesses of the standard curriculum in circuits and systems. For example, a top-10 list of questions for traditionalists might consist of:

1) Do your sophomores know what a circuit is used for? (Or can they only solve for node voltages and loop currents?)

2) Do your sophomores understand the difference between circuit models and the circuits themselves? (Or do they think a battery is an ideal source and that they can purchase a dependent source at Radio Shack?)

3) Do your students understand that frequency response characterizes *real circuits* and not just abstract systems?

4) Can your students map a transfer function to an implementation, even in a straightforward, nonoptimal way?

5) Can your students *design* a simple filter? (How do you choose the coefficients in the transfer function? Have they even thought about this?)

6) Have your students constructed a filter and *heard* its frequency response?

7) Are your students confused over the large number of different transforms they see in your signals and systems course?

8) Do your students understand how complex signals and complex impulse responses relate to real circuits?

9) Can your students explain the operation of an AM radio?

10) Do your students overwhelmingly rush to take a DSP course? (At Illinois, 80% do.)

In overcoming these weaknesses, the new ECE 210 was designed to address important, fundamental goals:

- Introduce signal processing and systems concepts earlier in the curriculum
- Increase students' motivation and learning by making applications of the material integral to the course
- Provide more rounded learning by integrating theory, applications, implementation, and hands-on experiences

In addition, any revision had to satisfy several challenging constraints:

- Streamline the curriculum by reducing both the total hours and the prerequisite courses
- Mesh with the popular new freshman EE course
- Retain the fundamentals in circuits and systems, and
- Serve as an effective prerequisite for the majority of courses in the EE curriculum

Any successful innovation at the introductory level had to work within the curriculum as a whole. Innovative introductory courses at some institutions have ultimately failed due to similar constraints.

3. THE NEW SOPHOMORE-LEVEL COURSE

ECE 210, Analog Signal Processing, is our answer to the goals and challenges described above. A more conventional name for the course would be "Analog Circuits and Systems," as it combines in one course key material from both the traditional sophomore circuits course and the junior systems course. However, in ECE 210 we stress that circuits are used to process signals and we spend time on applications and design. An outline of ECE 210 is given in Table 1.

Topic	Hrs.
Introduction to Signal Processing Systems	1
Review of DC Circuit Analysis: KCL, KVL, Dependent Sources	5
Capacitors and Inductors as Circuit Elements	2
Differential Equation Models, Transient and Steady State Response, Op Amps	6
Complex Numbers	2
Phasor Method for Sinusoidal SS	2
Laplace Transform Solution of Diff. Eqs., Impedance, Transfer Function	6
Linearity, Time-Invariance	2
Impulse Response and Convolution	5
Stability	2
Transfer Function Implementation and Block Diagrams	1
Fourier Series	5
Fourier Transform Basics	4
AM Radio	3
Filters and Filter Design	4
Sampling Theorem and Overview of Digital Signal Processing	1
Exams and Review	7
Total Hours	58

Table 1: Outline for ECE210, Analog Signal Processing

ECE 210 is a 4-hour, 15-week course. The course begins by covering material on circuits and op-amps, so that circuits can be used as examples of signal processing systems, and concepts of frequency response in actual circuits can later be stressed. To a first-order approximation, the remainder of the course comprises the analog topics from the traditional junior-level signals and systems course. Unlike the traditional course, however, we make a serious effort to relate the mathematical material to physical systems. This is partly done through a small set of laboratories, described in the next section. Also, in lecture, we thoroughly study AM demodulation and the superheterodyne receiver, and discuss simple analog filter design based on the linear circuit theory learned in the course. This nicely pulls together all of the elements of the course and highlights the interaction between theory and application, system concepts and their actual implementation as circuits, and ideal and practical designs. A heavy emphasis in the course is placed on Fourier analysis and frequency response, with AM radio serving as a vehicle for motivating Fourier concepts, exercising them, and relating them to practice via the circuit theory learned earlier in the course.

4. LABORATORIES

To improve student understanding of the abstract material in ECE 210, we have incorporated a set of five two-hour laboratories. The laboratory component was carefully constructed to minimize the student's time commitment in an already intensive course while offering hands-on, experiential illustration of the key abstract concepts in the course. The labs cover the following topics:

- RC filter time constant and frequency response
- Op amp amplifier and integrator
- Convolution
- Fourier series and band-pass filter
- Fourier transforms and AM radio

The last two laboratories are particularly exciting. In the Fourier series lab, students build an op-amp band-pass filter and measure its frequency response by sweeping the frequency of a sinusoidal input. Not only do students see the frequency response on an oscilloscope; they also hear the magnitude of the frequency response from a speaker connected to the output of the filter. The students then apply a square wave and sawtooth wave to the filter, where they have previously calculated the Fourier series for these waveforms. Depending on the fundamental frequency of the applied input, students may observe a sinusoidal output at the fundamental or one of the harmonic frequencies. They are asked to explain the outputs they observe, based on their Fourier series analysis.

In the final laboratory, the students study Fourier transforms of both baseband and AM modulated signals using a signal generator and an oscilloscope with an FFT module. They then "build" an AM radio superheterodyne receiver by connecting prefabricated modules. They observe both time- and frequency-domain waveforms at various points in the receiver and are asked to explain what they see, based on properties of the Fourier transform.

Some students object to the use of prefabricated modules after having built the circuits from the ground up in the previous labs. We are experimenting with using inexpensive high-frequency op-amps to simplify the radio design to the point that a working superheterodyne radio receiver, that the students can fully understand and analyze at the circuit level, can be breadboarded in less than an hour. If successful, this will further enhance the laboratory experience.

The five two-hour laboratories are offered over a ten-week period with each lab repeated in two consecutive weeks. The students are divided into two groups with each group attending lab every other week. This provides a more uniform loading throughout the semester both on the students and on the staff and facilities, thereby allowing us to squeeze the 210 labs into existing lab facilities. The laboratories for ECE 210 require substantial resources in terms of space, equipment, and faculty and TA time. However, we find that the effort and expense are repaid many times over in improved student understanding. Many "lights go on" during lab sessions. If the expense of lab staffing or equipment were a concern, some of the same benefit could be obtained by simulating the labs with one of the commercial software packages available for this purpose.

5. WHY ANALOG BEFORE DIGITAL?

The introduction of ECE 210, Analog Signal Processing, was probably our riskiest change in the new EE curriculum at Illinois, and it certainly had the largest ramifications in terms of the impact on the remainder of the curriculum. Alteration of the traditional circuits course is especially difficult because of the central role it plays as a prerequisite for many advanced EE courses.

Since the 1970's there have been numerous proponents of teaching DSP to sophomores. Perhaps the most outstanding older texts in this regard are those by Steiglitz [6] and Strum and Kirk [7]. The recent Georgia Tech initiative represents a significant new development in this direction [8]. However, the earlier texts have not led to widespread curriculum changes. Two possible explanations come to mind. First and foremost, it is important that a sophomore course in electrical engineering serve as a cornerstone for the rest of the curriculum. The standard circuit analysis course has done so for the following areas: electronic circuits (circuit analysis, frequency response), electromagnetics (phasors, capacitance, inductance), solid state electronics (differential equations), power systems (circuit analysis, complex numbers, phasors, transformers). Our new ECE 210 still prepares students for these courses, but also provides a firm foundation for the study of digital signal processing.

There is a second strong argument for treating analog signal processing prior to digital signal processing. Students enter our universities with well developed concepts of analog frequency from their trigonometry and physics courses. By contrast, the concept of digital frequency is entirely foreign. Humans perceive the physical world to be analog. From this perspective, it is not possible to fully comprehend digital signal processing without considering a complete system composed of an A/D, digital filter, and D/A. A full analysis of such a system requires prior exposure to Fourier transforms and the concept of analog frequency response. We, therefore, are proponents of teaching analog concepts prior to digital concepts, for pedagogical reasons.

In summary, our view is that analog material is needed for many subsequent EE courses and that few curricula can afford to spend hours at the sophomore level teaching both analog and digital courses, or to push most required courses back another semester until the analog material is taken later. It will be interesting to see how the innovative "DSP First" [8] approach works in terms of a total curriculum. From our perspective, it would be highly enjoyable to teach DSP first, but we find the arguments for analog first to be far more compelling.

6. REFERENCES

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