# ANALOG SIGNAL PROCESSING: A REPLACEMENT FOR THE SOPHOMORE-LEVEL CIRCUIT ANALYSIS COURSE

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## ABSTRACT

A new undergraduate curriculum in electrical engineering has been adopted by the Department of Electrical and Computer Engineering at the University of Illinois. Major changes have been incorporated, including a redistribution of the circuits and signal processing topics within the curriculum. After giving an overview of the new curriculum, this paper focuses on a new, required sophomore-level course on analog signal processing. This course combines material from the traditional course on circuit analysis with material on continuous-time signals and systems. Students completing this course can study digital signal processing as first-semester juniors, which leaves ample time for more advanced signal and image processing courses in future semesters.

## 1. INTRODUCTION

Undergraduate curricula in electrical engineering, at most universities, are relatively unchanged from 30 years ago. This is remarkable, considering that the field of electrical engineering has undergone a revolution over the past 30 years. In response, the Department of Electrical and Computer Engineering (ECE) at the University of Illinois has adopted a new curriculum. Among the many changes, the traditional sophomore-level circuit analysis course, and the junior-level signals and systems courses are being phased out, with the material in these courses redistributed within the curriculum in a new way. Some of the circuits material, and the analog part of the signals and systems material, have been incorporated into a new sophomore-level course on analog signal processing, ECE 210, which occupies the same slot in the curriculum as the old circuit analysis course. Other material in the circuit analysis course has been moved to the junior-level electronics course (which is no longer required - read on!) and to a new introductory course in the power 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 "semi-required" courses, as will be explained later.

The following sections of this paper introduce our new curriculum and provide some of the rationale for the changes. We then focus on the new ECE 210. Parts of this paper appeared earlier in [1].

## 2. DETAILS OF THE NEW CURRICULUM

Table 1 summarizes the new curriculum, by semester.

| | | | |
|---|---|---|---|
| Semester 1 | | Semester 2 | |
| Calculus I | 5 | Calculus II | 5 |
| Chemistry I | 4 | Physics I | 4 |
| Rhetoric | 4 | Intro to ECE | 4 |
| Elective | 3 | Elective | 3 |
| Semester 3 | | Semester 4 | |
| Diff. Equations | 3 | Physics III | 4 |
| Physics II | 4 | Computer Prog. | 1 |
| Comp. Sci. I | 3 | Analog Signal Processing | 4 |
| Electives | 6 | Comp. Eng. I | 3 |
| | | Electives | 4 |
| Semester 5 | | Semester 6 | |
| Intro to Electromag. | 3 | Advanced Core | 3 |
| Solid State Devices | 3 | Advanced Core | 3 |
| Probability | 3 | Electives | 10 |
| Digital Systems Lab | 2 | | |
| Electives | 5 | | |
| Semester 7 | | Semester 8 | |
| Senior Design Lab | 2 | Electives | 16 |
| Advanced Core | 3 | | |
| Electives | 11 | | |

**Table 1: Revised Electrical Engineering Curriculum**

The major changes from our current curriculum are:

- Freshman course on electrical and computer engineering is added
- Chemistry II is not required
- Sophomore-level circuit analysis course abolished, with material diffused into the remainder of the curriculum
- New course on analog signal processing, ECE 210, is required; combines elements of current sophomore-

level circuit analysis and analog parts of the junior-level linear systems course

- Junior-level linear systems course abolished, discrete-time material moved to our DSP course; DSP is placed on a list of five "advanced core" courses, from which students must take at least three
- Digital systems laboratory is required
- Probability and statistics is required
- Courses on electronics and electromagnetic waves no longer required, but placed on the list of five advanced core courses; list of five advanced core courses is given in Table 2
- ECE electives increased from 15 to 22 hours (including courses from the advanced core)
- Other technical electives decreased from 21 to 15 hours
- Free electives increased from 6 to 12 hours

| | |
|---|---|
| Digital Signal Processing | 4 |
| Electronic Circuits | 4 |
| Electromagnetic Waves | 3 |
| Power Circuits and Electromechanics | 3 |
| Comp. Eng. II or Comp. Sci. II | 3 |

**Table 2: Advanced Core (3 out of 5)**

The freshman course on electrical and computer engineering serves to introduce students to a broad spectrum of topics in electrical and computer engineering. This laboratory oriented course provides students with considerable experience in design and problem solving with electrical devices and systems [2]. The course is directed toward the design of an autonomous electric vehicle, with topics in lecture covered as they are needed in the laboratory. The goals of this course are to motivate the study of mathematics and physics, to help students decide on a major, and to help students appreciate the relationships among the various subdisciplines within electrical and computer engineering. This course has received overwhelmingly favorable comments from students.

The requirement of a second course in chemistry was abolished, to provide students more flexibility in choosing science courses. Students now have the option of replacing the second chemistry course with a course in modern biology, or physiology, or other such courses.

The rationale for the rearrangement of the circuits and signal processing topics will be given in the next section. To some extent, this rearrangement interfaces with the new 3-of-5 list of advanced core courses. Two of the courses on this list (Electronic Circuits and Electromagnetic Waves) were required in our old curriculum. Other courses on the list include DSP, which is already taken by half of our students as an elective, a second course in computer engineering or science, emphasizing programming of real-time systems, and an introductory course in power systems. This list of 5 advanced core courses is viewed by the faculty as being semi-required, in the sense that a strong argument can be made for placing each of these courses in the required curriculum. This temptation has been balanced, however, by the realization that the field of electrical engineering is now so broad, that we cannot hope for most of our students to gain in-depth exposure across the board. Thus, in cases where students will already have some previous exposure to a subject area in the required curriculum, we placed "essential" follow-on courses in the advanced core.

The motivation for requiring a course on probability and statistics was two-fold. First, exposure to probability and statistics is arguably an important component in the education of any scientist or engineer. Second, new ABET standards suggest some coverage of statistics.

Eighteen hours of the electives shown in the curriculum must be selected from an approved list of humanities and social sciences. One elective course must be drawn from a list of Science courses, and one from a list of Composition II courses. Other minor restrictions also apply.

## 3. CIRCUITS AND SIGNAL PROCESSING

Why rearrange the circuits and signal processing topics within the undergraduate curriculum? Ronald Rohrer deserves credit for coloring my thinking on this subject. Some years ago, Ron was barnstorming around the country, suggesting that the first course in electrical engineering be on the subject of signal processing, rather than circuits [3, 4]. At the time, I played the devil's advocate in the question and answer sessions that followed Ron's talks, by seemingly arguing in favor of the status quo. Privately, however, I sympathized with Ron's views. I am sure that I do not recall all of the rationale that Ron so eloquently laid out in his supporting arguments. I do recall, however, his insistence that incoming students have had vastly different exposure to engineering concepts than students from 30 years ago. In the 1960's, many (if not most) students had tinkered with circuits, and often with ham radios and automobile engines. These students were hands-on types. They were curious about circuits. Furthermore, electronic systems of the day were typically composed of discrete components, where the measuring points for voltages and currents were accessible. Circuit analysis was a very reasonable place to begin an electrical engineering curriculum! Times have changed. Incoming students now have experience with complex electronic systems, where the individual components are inaccessible. These systems are typically computers or consumer electronics equipment, which process audio and video signals. There are few discrete components. Incoming students have not built computers, VCRs, or CD players, as students used to build crystal radios. Furthermore, circuit analysis *per se*, is now practiced by only a small number of electrical engineers. The IC industry is fed by a handful of hot-shot circuit designers, who make heavy use of CAD software. Conversely, the number of engineers actively engaged in signal processing has skyrocketed. Many of these engineers are writing code for DSP microprocessors, which today *is* signal processing! Given the ubiquitousness of signal processing, and the fact that this subject is better matched to the experience level of our incoming students, why not teach signal processing first? This also leaves more time for students to take follow-on courses, such as a digital signal processing laboratory, image processing, speech processing, and medical imaging.

## 4. ANALOG VERSUS DIGITAL SIGNAL PROCESSING AT THE SOPHOMORE LEVEL

Since the 1970's there have been numerous proponents of teaching DSP to sophomores. Perhaps the most successful texts in this regard are those by Steiglitz [5] and Strum and Kirk [6]. However, these fine texts have not led to widespread curriculum changes. Perhaps they were written ahead of their time (although [6] is comparatively recent). Another possible explanation is that digital signal processing cannot be fully understood until one has acquired a background in analog signals and systems. Indeed, this is my conviction. I have found no way to make DSP totally understandable to students, without considering a complete digital system composed of an A/D, digital filter, and a D/A. Analysis of such a system in the frequency domain requires prior exposure to Fourier transforms and the concept of analog frequency response. I find that the analog side is the place to start, because students are already familiar with analog frequency from their trigonometry and physics courses. Combining analog experience with an in-depth treatment of an A/D, digital filter, and D/A, I find it is then easy to explain the concept of digital frequency. Without this approach, students have difficulty. Using illustrations, such as that of a slowing wagon wheel being sampled at 30 frames per second (and sometimes appearing to rotate forward and sometimes backward) illuminates the subject, but still does not evoke complete understanding. I find that the A/D and D/A interface is critical to a full understanding of DSP systems as used in practice. Thus, I am a strong proponent of teaching analog concepts prior to digital concepts.

There is a second, equally important, reason for teaching analog signal processing before DSP. A sophomore-level course should serve as a cornerstone for the electrical engineering curriculum. This is best done with an analog course. Our ECE 210 covers information that is pertinent to the following required or semirequired courses:

- Electromagnetics (phasors, capacitance)
- Solid State Electronics (differential equations)
- Electronic Circuits (circuit analysis, frequency response)
- Power Systems (circuit analysis, phasors)
- Digital Signal Processing (*many* topics from ECE 210)

## 5. DETAILS OF THE NEW SOPHOMORE-LEVEL COURSE

The outline of ECE 210 is given in Table 3. This 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 linear systems, and concepts of frequency response can later be stressed. The remainder of the course comprises the analog topics from our old junior-level signals and systems course, which covered both analog and discrete material. (As mentioned earlier, the discrete material has been moved into our DSP course, which is expanded from 3 to 4 hours.) Unlike our junior-level course, however, we make more of an 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. In the future, we plan to add a small amount of introductory material on analog filter design and then have students design analog filters to match prescribed frequency responses. The design process will be comprehensive, including choosing the coefficients in the transfer function, mapping the resulting transfer function to an op-amp filter structure, and the construction and characterization of the filter. A heavy emphasis in the course is placed on Fourier analysis and frequency response.

| Topic | Hrs. |
|---|---|
| Introduction | 1 |
| Review of DC Circuit Analysis: KCL, KVL, Dependent Sources | 5 |
| DC Op Amp Circuits | 1 |
| Capacitors and Inductors as Circuit Elements | 2 |
| Differential Equation Models, Transient and Steady State Response, Op Amps | 7 |
| Complex Numbers | 2 |
| Phasor Method for Sinusoidal SS | 2 |
| Linear Time-Invariant System Definitions | 2 |
| Impulse Response and Convolution | 6 |
| Functions of a Complex Variable | 1 |
| One-Sided Laplace Transform | 4 |
| Laplace Transform Solution of Diff. Eqs., Impedance, Transfer Function | 3 |
| Transfer Function Implementation and Block Diagrams | 2 |
| Stability | 2 |
| Fourier Series | 5 |
| Fourier Transform Basics | 4 |
| AM Radio | 2 |
| Distortionless Transmission and Practical Filters | 3 |
| Sampling Theorem and Overview of Digital Signal Processing | 1 |
| Exams | 3 |
| Total Hours | 58 |

**Table 3: Outline for ECE210, Analog Signal Proc.**

## 6. LABORATORIES

To improve student understanding of the abstract mathematical material in ECE 210, we have incorporated a set of five laboratories during the second half of the semester. The labs cover the following topics:

- RC time constant and frequency response of an RC filter
- Op amp amplifier and integrator
- Convolution
- Fourier series
- Fourier transforms

The last two laboratories are particularly exciting. In the Fourier series lab, we have 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 saw-tooth 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 at one of the harmonic frequencies. They are asked to explain the outputs they observe, based on their Fourier series analysis.

In the last 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.

Admittedly, the laboratories for ECE 210 require sophisticated (and expensive) equipment, and considerable 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.

## 7. MATHEMATICAL PREPARATION

We conclude this paper with some comments and observations on the mathematical preparation of our sophomores at the University of Illinois. At least as measured by faculty expectations, the mathematical skills of our students are mediocre (on average). Most of our students have blazed their way through calculus and differential equations (including lots of advance placement (AP) credit) and yet still have serious gaps in their understanding. Thus, the reader might reasonably ask, "You are teaching Fourier transforms to this crew?" My answer is, "Absolutely!" Our students must learn mathematics more completely at some point. Why not take on this project as soon as they have finished their calculus and differential equations courses? Why wait?

I have taught ECE 210 twice now, and based on student outcomes on exams, it is clear that the majority of sophomores can learn convolution, Laplace transforms, and Fourier transforms quite well. However, this does not come without some patience (and good humor) on the part of the instructor. At the beginning of the semester, I poke fun at my students (many of whom have straight A's in their math courses), telling them that I am fully aware that they do not yet know calculus, but that they will by the end of the semester. I take care to insert certain course topics and homework problems to give students practice in areas of mathematical weakness. I introduce complex numbers, complex-valued signals, and functions of a complex variable in great detail, making sure to treat all complex quantities as ordered pairs of real quantities, so that the mystery is removed in the notation $j = \sqrt{-1}$. I introduce the impulse distribution in a rigorous way, although I carry this no further than needed for the purpose of the course. Overall, my students are far more mathematically sophisticated coming out of ECE 210 than they were entering. Despite this, we should not set our expectations too high. I do not claim that the mathematical abilities of my students are equal to those of students who have completed a junior-level signals and systems course. I only maintain that they are close. All students aspiring to work on the signals and systems side of electrical engineering must take courses in DSP, communications, control, etc. to further improve their mathematical skills.

## 8. REFERENCES


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