

INTRODUCTION TO DIGITAL SIGNALS AND FILTERING: IMPLEMENTING “DSP FIRST” AT THE UNIVERSITY OF OKLAHOMA

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ABSTRACT

We first discuss the curricular revisions required to implement “DSP First” in both the Electrical and Computer Engineering B.S. degrees at the University of Oklahoma. We follow this by describing our experiences over the past two years using this approach to education. We have noticed that students tend to select DSP projects in two digital systems courses, “Microprocessor System Design” and “Digital Design Laboratory.” We want to further encourage this interaction of the digital circuit courses with the digital signals and systems courses. To this end, we have recently proposed the following: the traditional approach to engineering education is to first teach implementation theory and then teach system theory—so we taught circuit theory and then system theory. We propose to change our current course sequences to follow this model, but with a focus on digital implementation techniques. At the University of Oklahoma, we begin with an introductory digital design course and a course on digital systems and filtering. We then move into system theory and microprocessor system theory. At the senior-level, we propose an integrated sequence that considers algorithms and implementations as inseparable.

1. INTRODUCTION

The Electrical and Computer Engineering program at The University of Oklahoma has recently (Fall 1998) adopted an introductory course, ECE 2713 Digital Signals and Filtering, as one of two “gateway” courses into both programs. The other gateway course is ECE 2213 Introduction to Digital Design. The curriculum for each of the programs is given in Figure 1.

Students in both curricula take ECE 2713, Digital Signals and Filtering, before taking a course in analog circuits (ENGR 2613, Introduction to Electrical Science). The EE students take an additional course in circuits, ECE 3723, as a follow on to Electrical Science. All students (CpE and EE) take the ECE 3793 Signals and Systems course, and then they may choose electives that follow these courses, such as ECE 4213, Digital Signal Processing.

To examine the curricular issues at hand, we first describe our implementation of the “DSP First” content in ECE 2713. We follow this with some discussion of the student and faculty perceptions. Next, we describe the impact this course has had on

the analog circuits development and offer our proposal for integrating the digital circuits and the systems courses. We close by summarizing our ideas and providing a challenge.

2. ELEMENTS OF ECE 2713

2.1 ECE 2713 Course Content

The following sequence of topics is typically presented in the ECE 2713 course:

- Define signals and systems
- Use complex numbers
- Use MATLAB®
- Define real sinusoids
- Define complex sinusoids
- Define amplitude modulation
- Use periodic waveforms
- Define Fourier series
- Understand time/frequency representations
- Define frequency modulation
- Understand sampling and A/D conversion
- Understand D/A conversion

REVIEW

Midterm Exam I

- Define FIR filters
- Use FIR filters
- Implement FIR filters
- Perform FIR convolution
- Develop FIR filters
- Determine FIR sinusoidal response
- Determine FIR responses
- Use FIR frequency response

REVIEW

Midterm Exam II

- Use FIR example filters
- Define the Z-transform
- Use Z-transform properties
- Use simple filters
- Determine IIR filter output
- Implement IIR filters
- Understand IIR system properties
- Determine inverse Z-transforms
- Determine IIR filter response via transforms

- Use 2nd-order IIR filters
- Use IIR examples

REVIEW

Midterm Exam III

- Define spectral estimation
- Define the DFT/IDFT
- Define the FFT/IFFT
- Use the periodogram and spectrogram

Comprehensive Final Exam

The first set of topics prepares the students to examine time functions and introduces the notion of frequency. The second set of topics introduces formal descriptions of FIR filters in time and in frequency (convolution and frequency response). The third set of topics introduces the notion of complex frequency (and transfer function) with the added complexity of having IIR filters. Finally, spectral analysis from a deterministic standpoint is introduced.

For one not familiar with the textbook [DSP First: A Multimedia Approach](#) [1], the presentation sequence above follows the chapters in that text very closely. This sequence of topics has evolved slowly over the past several years to reflect our changing perception of student backgrounds and interests. These issues will be discussed below.

The class sections average approximately 50 students. The course is formally a “laptop” course – The University of Oklahoma College of Engineering has a laptop computer requirement for all incoming students. Thus, students have the ability to examine notes online, and to run MATLAB in class.

2.2 Student Perceptions

Student perceptions follow two typical paths – either the student perceives the mathematics as being very difficult, and thus that the topics are tedious; or the student perceives little difficulty in understanding the mathematics, and thus can describe rationally and with a high degree of perception the utility of the topics in many relevant products and systems. Only one student has not followed this pattern – an athlete on (track) scholarship who found the mathematics difficult but was nonetheless able to pose deep questions, and respond verbally with some significant insight.

Some students have taken the ENGR 2613 course previously (nothing in the prerequisite structure prevented this until the Fall 2000 semester). This has not appeared to have significant influence on performance, either positively or negatively. The students from the first year have indicated in significant numbers that having ECE 2713 improved their performance in the latter courses in the circuits and systems sequence.

2.3 Student Preparedness

First and foremost, the importance of mathematics, and the sequencing of the mathematical topics in the curricula are of

crucial importance in student performance in ECE 2713. Several of these key issues are:

1. Complex numbers
2. Sums and series
3. Limits
4. Differential (difference) equations

Each of these issues has different symptoms and consequences which we examine in turn next.

A significant portion (~15%) of the students has not seen complex numbers prior to entry into the course. We are initiating an examination of this phenomenon – preliminary results indicate a general “dumbing down” of the primary calculus texts to push complex numbers to the back chapters, and thus many students may either get only a superficial treatment of them, or no exposure to them at all. This is a significant problem with implications for many courses in Electrical and Computer Engineering, not just ECE 2713.

Almost none of the students entering ECE 2713 have seen series and summations. This influences how we teach the Euler identity, as well as how we present the geometric series for finite and infinite length summations. This is apparently a timing issue for the majority of our students – the requisite material is incorporated into the Calculus course that they take simultaneously with ECE 2713 – and so is not a significant problem. We have considered, but not implemented, requiring this calculus course as a co-requisite course to alleviate the problem for all students.

The lack of series and summations knowledge also detracts from the students’ abilities to handle sequence limits. In particular, students are unfamiliar with L’Hospitals rule, and the growth/decay rates of time series and functions. This impacts their ability to understand stability and their ability to appreciate convergence in the Z- and Fourier Transforms. Even simple ideas cause problems, *e.g.*, the sequence $e^{j\omega n}$ is often not viewed as a bounded, oscillatory sequence of numbers (real and imaginary). Even the concept that the magnitude of $e^{j\omega n}$ is constant remains unclear to many students.

Finally, the solution to linear, constant coefficient difference equations is not very well understood by the students at this time because they have not been exposed to differential equations in their mathematics courses. Thus, many students do not view the exponential function to be of any particular importance above other functions.

MATLAB causes problems only to students who cannot seem to view data as a vector or matrix. These same students, when allowed to use “for loops” to deal with the variables as scalars, often can complete assigned projects. Their programs run slower, but the results are still valid. We are considering this issue from a deeper perspective – but time to teach vectors and matrices in this course is limited.

3. IMPACT

3.1 Curricula

Now that we have observed the course ECE 2713 and its particular content and issues, we turn to the impact of this course on the later courses in the two curricula. We categorize the impact under two main concerns:

1. Analog circuits and systems
2. Integration of digital circuits and the circuits and systems sequence

We study each of these in turn.

3.2 Changes in analog circuits and systems

During the first year that ECE 2713 was implemented in both curricula, a consensus emerged among those faculty who self-identified as electrical as opposed to computer engineers that a second follow-on course in analog circuits was needed for the EE curriculum. This was added, and is shown in Figure 1b. as ECE 3723 Electrical Circuits. Only EE students take this course, and it is taken following the ENGR 2613 course that is taken by both EE and CpE students. This change is still rippling up through both curricula, not least because there is now a lack of consensus regarding the content of the ENGR 2613 course. This problem is emerging as one of the most critical problems in the CpE curriculum.

One approach that might solve this problem is a more targeted textbook for ENGR 2613. Traditional circuit texts, such as that currently used at The University of Oklahoma [2], are most often constructed for a full year (2 semester or 3 quarter sequence) course. However, this text can be used to construct a one-semester course that introduces the basics (circuit elements and analysis), followed by Laplace transforms, operational amplifiers, two-port networks, and AC circuits. An alternative approach is embodied in the newer text [3] that is designed for learning digital circuits concurrently with analog circuits. Circuit theory is taught to “get across the ‘analog stuff’ in such a way that our students will see exactly what it is good for, and maybe even learn something from it [3].” The text develops fundamental electrical concepts (e.g. units, elements, and basic circuit laws) first, and then moves onto RC circuits and interconnect, fanout and capacitive coupling, RLC circuit analysis, networks and transmission line theory, before ending with time- and frequency-domain signal representations (e.g. transforms).

3.3 Integrating the digital circuits

Recently, a national need has emerged for Digital Signal Processing (DSP) engineers who can design and implement DSP algorithms. Traditionally, the design and implementation parts of the system would be spread between two or more people, *e.g.*, one engineer to design the algorithm and another to implement the algorithm. Universities have traditionally produced graduates with one expertise or the other. As DSP has been introduced earlier in the curriculum, however, more undergraduate students

are familiar with DSP algorithms. Although most electrical and computer engineering majors have some knowledge about digital design and microprocessor implementation techniques, they have little understanding of how the design and the implementation of an algorithm affect one another. In fact, it is only recently that implementation considerations have become a part of algorithm design. Even so, they are often treated at a naïve level, such as counting FLOPS (which can be conveniently determined by Matlab®). Viewing this situation, we have recently proposed a primary goal of educating Digital Signal Processing (DSP) engineers who can develop algorithm designs and implementations.

To accomplish this broad goal, we have identified several specific objectives that we wish to accomplish as we modify the courses in our existing electrical and computer engineering curricula:

1. Integrate design and implementation throughout the systems and digital sequences by teaching how the areas affect one another.
2. Increase retention of non-traditional students by increasing the perceived relevance of our courses and, thus, student interest in those courses.
3. Remove artificial barriers in curricula that lead to distinct separation of closely related courses.

These objectives directly support our goal of producing DSP engineers who not only can implement DSP designs, but also can design DSP algorithms with an understanding of how the implementation affects the design.

The traditional approach to engineering education is to first teach implementation theory and then teach system theory—so we taught circuit theory and then system theory. We propose to change current course sequences to follow this traditional model; we will teach implementation theory first, but today with a focus on digital techniques. Circuit theory is retained to support the understanding of how digital approaches work. We begin with an introductory digital design course and a course on digital systems and filtering and then move into system theory and microprocessor system theory. At the senior-level, we propose an integrated sequence that considers algorithms and implementations as inseparable.

Industry representatives have indicated that there is a significant need for students with the ability to design *and* implement DSP algorithms. In 1998, integrated circuits for DSP were a \$10B industry [4]. Often they hire computer engineering undergraduate students and then have them take graduate courses in digital signal processing. Even after taking graduate courses, the working engineers still require special seminars or industry experience to integrate the skills they have learned in the classroom. Similar problems exist in graduate school—it is difficult to find students with good implementation abilities and an understanding of algorithm design. However, the biggest problem with the education of DSP engineers for both industry and graduate school is the lack of knowledge integration. Electrical and computer engineering graduates rarely have the

ability to implement DSP algorithms. Consequently, we have come to believe that without the ability to implement algorithms, the ability to design algorithms is seriously degraded.

Unfortunately, there are very few faculty with broad knowledge of both DSP algorithm design and implementation techniques. Some algorithm designers use digital signal processor chips to implement their designs. However, with applications requiring high throughput rates and the prevalence of field programmable gate arrays, all the rules change. Simply counting FLOPs is naïve. Even with DSPs, the intricacies of pipelining and memory access patterns should be considered. Only recently have we started producing graduate students with the necessary skill set. In addition, while digital design experts can efficiently implement algorithms, they can rarely identify different algorithm approaches that would be better suited for a particular implementation technique, because they lack an understanding of the choices and effects of the algorithm design decisions (e.g. stability, convergence, quantization effects).

We want our undergraduate students to integrate the knowledge of our systems sequence with the knowledge of the digital design sequence to better understand both areas. In addition, by relating classes to one another, we hope that students will gain experience in the integration of knowledge across the curricula. We think that this integration of knowledge will produce DSP engineers who can design algorithms and implementations with an understanding of how the implementation affects the design and how the design affects the implementation. To produce undergraduate students with these capabilities, we need educational materials that will support the delivery of relevant course content. However, faculty also need the opportunity to update their abilities to incorporate these recently emerging areas, as well as educational materials that can be used in the existing curricular structure.

Overview: To achieve our goal of providing education to electrical and computer engineering students so that they can become DSP engineers with knowledge of both algorithm design and implementation, we have identified areas where we can integrate the ideas into our existing curricula. Both our CpE and EE students take two sequences of courses that are the target of our efforts: the “digital” sequence and the “systems” sequence, as shown in Figure 2. Our plan is to integrate these two sequences by creating a “companion” relationship between the sophomore and junior level classes. Then, at the senior-level an integrated course sequence will be created.

Specifically, we will use examples and assignments in our introductory digital design class and digital signals and filtering (“DSP First”) class to help students to see relationships between system design and implementation at an early level. Our electrical science course is a service course that will not be directly affected by our proposed changes. At the junior-level, we will create a similar companion relationship between the Signals & Systems class and the Microprocessor System Design class. The Signals & Systems class focuses on the design of linear and non-linear systems, while the Microprocessor Systems Design class focuses on hardware and software design, as well as interfacing. Both pairs of companion classes allow flexibility so

students can easily transfer from other universities and community colleges.

At the senior-level, we propose a much more radical, integrated approach. Instead of separate courses for teaching digital signal processing and for providing students with hands-on digital design experience, we plan to integrate digital design and DSP into a single 2-course sequence. This sequence can be either an elective sequence or a required sequence depending on the needs of a particular university. This sequence will provide not only digital signal processing theory, but also opportunities for students to implement DSP algorithms with digital signal processors (DSPs), field programmable gate arrays (FPGAs), and combinations of DSPs with FPGAs.

Expected Outcomes: In addition to the advantages to our students, we also plan to develop the following:

1. Innovative materials suitable for dissemination that incorporate effective teaching and learning strategies for combining DSP theory and implementation ideas.
2. Evaluation methods to determine the effectiveness of the materials and practices at different types of institutions serving students with diverse backgrounds and career goals.
3. A short course for faculty who are interested in incorporating our ideas into their curricula.

4. SUMMARY

Implementations of digital signal processing algorithms have recently undergone significant changes with the advent of field programmable gate arrays. Until recently custom VLSI and ASICs have been used when digital signal processors have not been able to meet speed requirements. However, the wide availability of powerful FPGAs has given designers the ability to use flexible FPGA implementations that can be easily programmed without costly fabrication cycles. With this ability to create faster implementations with the ease of field programmability, a large percentage of DSP algorithms now use FPGAs. Systems that combine the usage of DSPs and FPGAs are also becoming increasingly common. In 1998, digital signal processors were approximately 38% of the DSP integrated circuit market in dollars. Many of the remaining applications requiring custom circuits will be able to be implemented in FPGAs. An independent study by Forward Concepts in 1997 indicates that DSP engineers plan to use FPGAs as often as custom ICs. In addition, advances in DSP also are allowing more circuits to be implemented with digital signal processors. It’s estimated that, in 2002, 2 billion programmable Multiply & Accumulates (MACs) will be available for \$1 [4].

Unfortunately, academics generally separate ideas of digital design from those of digital signal processing. Without teaching our students how these two important areas impinge and interact, we cannot produce DSP engineers who have an understanding of how digital design and DSP algorithms affect one another. For example, when designing a DSP algorithm it is important to understand how the choice of using a DSP or an FPGA affects the results obtained. Also, engineers who design FPGA structures

(e.g. who work for Xilinx, Actel, Altera, etc.) must be aware of the needs of digital signal processing to produce FPGAs that can better meet algorithm requirements.

We feel that we have established a strong linkage between traditional sequences in systems and in digital design. Our first priority will be the integration of the senior-level courses. This activity was our initial avenue into this area. However, we soon realized that this change is, by itself, inadequate. Consequently, we are proposing changes throughout the undergraduate curriculum.

The first of these lower-division changes will be implemented in the sophomore-level courses, ECE 2713 and ECE 2213. Then, the junior-level courses will be adjusted to provide the “fit” between the sophomore and senior courses.

The most dramatic changes are occurring in Digital Signal Processing Education since the time of its incorporation into the graduate programs in the late 1960’s. DSP is becoming an “enabling” technology for many areas of industry, e.g., telecommunications, computers, multimedia, internet. We must

embrace these changes, and provide our students with the necessary tools to become highly successful engineers and entrepreneurs capable of continuing the growth in our high-tech industries. Our students who finish with a course in DSP who understand VHDL and other digital circuit design tools and methods are a key component of this work force. Let’s continue the progress we have made!

5. REFERENCES

- [1] J. McClellan, R. Schafer, and M. Yoder, DSP First: A Multimedia Approach, Prentice-Hall, New York, 1998.
- [2] J. Nilsson and S. Riedel, Electric Circuits, 6th edition, Prentice-Hall, New York, 1999.
- [3] M. Reed and R. Rohrer, Applied Introductory Circuit Analysis, Prentice-Hall, New York, 1999.
- [4] W. Roelandts, CEO, Xilinx Inc., “IC Technology Enables New Programmable DSP Solutions,” Plenary Speaker, *International Conference on Acoustics, Speech, and Signal Processing*, Phoenix, Arizona, 1999.

Year	FIRST SEMESTER	Hours	SECOND SEMESTER	Hours
FRESHMAN	ENGL 1113, Prin. of English Composition (Core II)	3	ENGL 1213, Prin. of English Composition (Core II)	3
	CHEM 1315, General Chemistry	5	MATH 2423, Calculus & Analytic Geometry II	3
	MATH 1823, Calculus & Analytic Geometry I (Core II)	3	PHYS 2514, General Physics for Engineering & Science Majors (Core III)	4
	HIST 1483, U.S., 1492-1865, or	3	P.S.C. 1113, American Federal Government (Core III)	3
	1493, U.S., 1865-Present (Core IV)	3	C.S. 1323, Fund. of Computer Programming	3
	ENCR 1112, Intro. to Engineering	2		
	TOTAL CREDIT HOURS	16	TOTAL CREDIT HOURS	16
SOPHOMORE	MATH 2433, Calculus & Analytic Geometry III	3	MATH 2443, Calculus & Analytic Geometry IV	3
	PHYS 2524, General Physics for Engineering & Science Majors	4	C.S. 2413, Data Structures	3
	C.S. 1333, Programming Structures & Abstractions	3	ECE 2213, Intro. to Digital Design	3
	C.S. 1813, Discrete Mathematics	3	ECE 2772, EE Laboratory I	2
	ECE 2713, Digital Signals and Filtering	3	ENCR 2113, Rigid Body Mechanics	3
			ENCR 2613, Electrical Science	3
	TOTAL CREDIT HOURS	16	TOTAL CREDIT HOURS	17
JUNIOR	MATH 3113, Engineering Math I	3	C.S. 3113, Intro. to Operating Systems	3
	+ECE 3223, Microprocessor System Design	3	*ECE 3793, Signals and Systems	3
	+ECE 3772, EE Laboratory II	2	*ECE 3872, EE Laboratory III	2
	+ECE 3813, Introductory Electronics	3	ENCR 3293, Applied Engineering Statistics	3
	ENCR 2213, Thermodynamics	3	ENCR 3723, Numerical Methods for Engineering Computations	3
	†Approved Elective, Core III: Social Science	3		
			†Approved Elective, Core IV: Artistic Forms	3
	TOTAL CREDIT HOURS	17	TOTAL CREDIT HOURS	17
SENIOR	C.S. 4263, Software Engineering I	3	*ECE 4773, Laboratory-Special Projects (Capstone)	3
	*ECE 4273, Digital Design Laboratory	3		
	*ECE 4613, Computer Architecture	3	*ECE/CS 3000-4000-level Elective	3
	*ECE/CS 3000-4000-level Elective	3	*Professional Elective	3
	†Approved Elective, Core IV: Western Civ. & Culture	3	†Approved Elective, Core IV: Non-Western Culture	3
	TOTAL CREDIT HOURS	15	TOTAL CREDIT HOURS	12

Figure 1a. CpE Curriculum

Year	FIRST SEMESTER	Hours	SECOND SEMESTER	Hours
FRESHMAN	ENGL 1113, Prin. of English Composition (Core II)	3	ENGL 1213, Prin. of English Composition (Core II)	3
	CHEM 1315, General Chemistry (Core III)	5	MATH 2423, Calculus & Analytic Geometry II (Core II)	3
	HST 1483, U.S., 1492-1865, or 1493, U.S., 1865-Present (Core IV)	3	P SC 1113, American Federal Government (Core III)	3
	MATH 1823, Calculus & Analytic Geometry I (Core II)	3	PHYS 2514, General Physics for Engineering & Science Majors (Core III)	4
	ENCR 1112, Intro. to Engineering	2	C S 1323, Fund. of Computer Programming	3
	TOTAL CREDIT HOURS	16	TOTAL CREDIT HOURS	16
SOPHOMORE	MATH 2433, Calculus & Analytic Geometry III	3	MATH 2443, Calculus & Analytic Geometry IV	3
	PHYS 2524, General Physics for Engineering & Science Majors	4	MATH 3113, Engineering Math I	3
	C S 1333, Programming Structures & Abstractions	3	ECE 2772, E E Laboratory I	2
	ECE 2213, Intro. to Digital Design	3	ENCR 2113, Rigid Body Mechanics	3
	ECE 2713, Digital Signals and Filtering	3	ENCR 2613, Electrical Science	3
	TOTAL CREDIT HOURS	16	TOTAL CREDIT HOURS	14
JUNIOR	PHYS 3223, Modern Physics for Engineers	3	*ECE 3113, Energy Conversion I	3
	*ECE 3223, Microprocessor System Design	3	*ECE 3323, Intro. to Solid State Electronic Devices	3
	*ECE 3613, Electromagnetic Fields I	3	*ECE 3723, Electrical Circuits	3
	*ECE 3772, E E Laboratory II	2	*ECE 3793, Signals and Systems	3
	*ECE 3813, Introductory Electronics	3	*ECE 3872, E E Laboratory III	3
†Approved Elective, Core III: Social Science	3	†Approved Elective, Core IV: Artistic Forms	3	
	TOTAL CREDIT HOURS	17	TOTAL CREDIT HOURS	17
SENIOR	ENCR 2213, Thermodynamics	3	ENCR 3723, Numerical Methods for Engineering Computations	3
	ENCR 3293, Applied Engineering Statistics	3	*ECE 4773, Laboratory-Special Projects (Capstone)	3
	*ECE 4273, Digital Design Lab	3	*ECE Elective	3
	*ECE Elective	3	*Professional Elective	3
	†Approved Elective, Core IV: Western Civ. & Culture	3	†Approved Elective, Core IV: Non-Western Culture	3
	TOTAL CREDIT HOURS	15	TOTAL CREDIT HOURS	15

Figure 1b. EE Curriculum

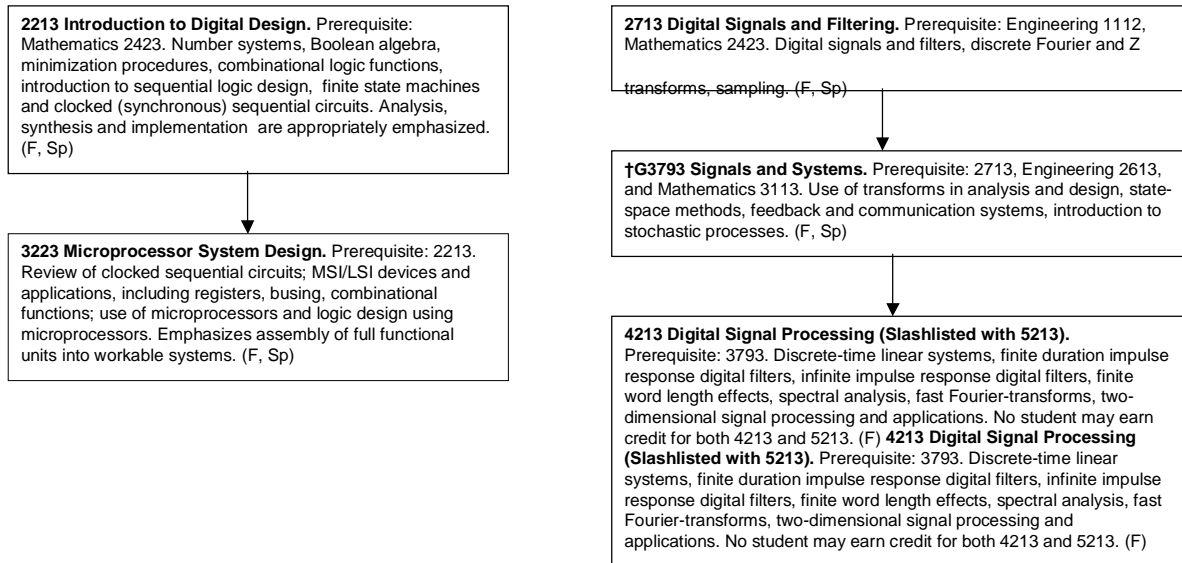


Figure 2. Systems and Digital Circuits Sequence