Connecting Theory to Practice in an Online Introductory Signals and Systems Course

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***Abstract*— This research to practice full paper presents the experience and evaluation of engaging students in a theoretical online signals and systems course through a set of application-oriented MATLAB lab exercises. Learning signals and systems concepts often poses challenges to students due to the abstract nature of the concepts and students' lack of prior experience. Many interventions have been proposed in the literature to address this issue with the goal of improving the student learning experience. The challenge is how to select/adapt these activities for use in a compact, accelerated online introductory signals and systems course, in which students have a wide range of prior experience and limited interactions with faculty and peer. Specifically, this paper will discuss how five MATLAB lab exercises were introduced to connect theory to practice. The impact of this addition was evaluated through student survey and grade analysis. Survey results showed that most students, regardless of course performance, enjoyed the labs. They acknowledged that the labs helped them solidify theory through practice and also helped them connect and apply signals and systems concepts to real world applications.**

Keywords—Distance, Open and Flexible Education, Laboratory Experiences, Electrical Engineering, Signals and Systems, First and Second Year Programs, Entrepreneurship Programs

I. Introduction

To meet the growing demand of online education, our large, public, research university (Arizona State University) has started a fully online ABET accredited electrical engineering undergraduate degree program in the fall of 2013 [1]. Our goal is to provide students with a flexible and accessible online learning environment with the same high quality education standards as the on-site students.

Keeping students interested and engaged is a challenge for educators, especially for online courses where face-to-face real time interaction with faculty and peers, which is required by many active learning techniques, is limited. An online introductory signals and systems course was traditionally taught using video lectures, examples, homework, quizzes and exams. Since the course is theoretical in nature, every term there were students inquiring about practical applications.

To bridge the gap between theory and practice, a series of application oriented MATLAB lab exercises was added to the curriculum. These lab exercises served three purposes. First, they helped students solidify difficult theoretical concepts through practical applications. Second, through story-telling, these hands-on exercises posed interesting, real-world hypotheticals and let students get a glimpse into how the theoretical concepts of signals and systems can be applied to solve real world problems, dispelling their common notion that signals and systems was nothing else but mathematics. Third, these exercises introduced students to three application areas of signals and systems including signal processing, control, and communication system, helping students connect this introductory course to additional advanced courses in the electrical engineering curriculum.

This paper will discuss how these application-oriented hands-on exercises were incorporated in the existing curriculum, specifically how five MATLAB based lab exercises were introduced to connect theory to practice. The impact of this addition will be evaluated through student survey and grade analysis. The rest of the paper is organized as follows. First, the prior work on signals and systems education is briefly reviewed in the background section. The lab design and implementation is described next, followed by the assessment and results. Then future work is presented, followed by conclusion.

II. Background

A. Existing Work

Learning signals and systems concepts often pose challenges to students due to the abstractness of the concepts and students' lack of prior experience [2]. Many interventions have been proposed in the literature to address this issue with the goal to improve student learning experience.

In [3], the authors interviewed students to identify the important and difficult concepts students perceived in a sophomore-level continuous-time signals and systems course. This knowledge can help instructors understand if their view of important concepts is aligned with students' view and can also help them allocate resources to the topics students struggle.

Demonstration was used as an effective way to promote interactive learning. A customized real-time DSP based software and hardware package [4] was developed to help instructors demonstrate digital signal processing concepts in the classroom.

In-class peer interaction exercises were used to improve student learning and motivation in [5]. Technology based teaching strategies including reuse of open source educational

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materials, interactive simulations, online homework and assessment were explored in [6].

Various lab-based exercises were developed to facilitate learning and connect theory to real-world applications including DSP hardware based labs [7] and an analog circuit based platform [8].

At the graduate school level, small group learning projects were used as a pedagogical tool to make signal processing more appealing in a master's degree program [9]. Students working in teams chose project ideas from a variety of practical applications including topics suggested by industry partners. They conducted research through technical report reading, proposed new software/solution to the specified problem, and presented their results through presentation and report.

All prior work discussed reported improvement in the student learning experience. The challenge is how to select and adapt activities to be used in a compact, accelerated online introductory signals and systems course, in which students have a wide range of prior experience and have limited interactions with faculty and peers.

In recent years, KEEN (Kern Entrepreneurial Engineering Network) [10] started a movement of fostering an entrepreneurial mindset in young engineers. The mission is to instill the mindset of curiosity, connections and creating values [11] throughout the undergraduate curriculum, with the ultimate goal to graduate engineers who can create personal, economic, and societal value through a lifetime of meaningful work. As a partner institution in the KEEN network, we are reviewing our curriculum. For a theoretical sophomore level course like the signals and systems, the first step to achieve the mission statement would be to cultivate students' curiosity and help them connect course concepts with applications that are meaningful to them.

B. *Online Course*

Signals and systems I at our university is a 3-credit hour course required by all electrical engineering students during their second year. It focuses on the basics of signals and systems including signal transformation, linear time-invariant systems, Fourier series, Fourier transforms, Laplace and Z transforms. After taking this fundamental course, students can take signals and systems II which is 4-credit hour lecture/lab pathway course to more communication, signal processing and controls area courses.

The 7.5-week online version of the course is part of the ABET accredited electrical engineering undergraduate curriculum which is available fully online. It covers content identical to the 15-week ABET accredited face-to-face version. The course focuses on theoretical concepts and does not have a lab component.

The online course was developed with input from an instructional designer. It consists of short ten to thirty minutes video lectures, practice problem handouts with step-by-step derivations, quizzes that provide instant feedback and a Piazza discussion forum [12] for student instructor and peer interactions. The exams are proctored through the online proctor service RPNow [13]. The course schedule is shown in Table I.

TABLE I. WEEKLY COURSE CONTENT

Week	Learning Objectives
1	Introduction to Signals and Systems
2	Linear Time-Invariant Systems
3	Fourier Series Representation of Periodic Signals
4	The Continuous-Time Fourier Transform
5	The Discrete-Time Fourier Transform and Sampling
6	The Laplace Transform
7	The Z-Transform
7.5	Final Exam

The online student population [1] is on average ten years older than on-site students, with 75% of online students from out-of-state and a third of them are either active military or veterans. Most students registered online work either full-time or part-time.

The course was first offered in the spring of 2015 and was subsequently offered and improved every semester since then. Student feedback about the course was overall positive. One consistent complaint was that the course was too abstract and theoretical. Students wanted examples on how to apply the signals and systems concepts to real world applications.

III. DESIGN AND IMPLEMENTATION

To avoid adding too much load to the already condensed schedule, MATLAB simulation labs were chosen as the vehicle to bridge the gap between theory and practice in this introductory signals and systems course. The goal was to use these simulation exercises to lay a good foundation so that students could handle more complex microcontroller and DSP hardware based applications in subsequent advanced courses.

Three application areas of signals and systems were identified as the focus areas for the labs: signal processing, control and communication systems. They were chosen to help students understand not only where signals and systems concepts can be applied, but also to help them see more easily the links between this introductory course and the more advanced courses.

Specifically, fives labs were added to the curriculum to align with the course learning outcomes and schedule, and to enhance understanding of student-perceived difficult concepts [3]. Audio signals were used in four out of the five labs due to their tangibility and simplicity [4, 7, 8, 9]. The learning objectives of the five MATLAB labs are shown in Table II.

TABLE II. LAB LEARNING OBJECTIVES

Lab	Week	Learning Objectives
1	1	Generate and play a digital audio signal by applying the concept of sampling. Implement time domain signal transformations and observe their effects.
2	2	Understand the concepts of system input, output and impulse response. Use convolution function to generate system output given input and impulse response.

Lab	Week	Learning Objectives
3	5	Compute, plot a digital signal's Fourier transform and observe the signal's spectrum in the frequency domain. Choose filter cutoff frequency to properly filter out unwanted components or characteristics.
4	6	Derive system transfer function for a feedback system. Practice tuning a PI controller and observe the impact of controller parameters on the performance metrics of a control system.
5	7	Derive Fourier transforms for signals involved in amplitude modulation and demodulation. Describe how amplitude modulation/demodulation works. Practice modulating and demodulating a signal. Properly resample signals during modulation and demodulation.

Students had varied MATLAB background prior to this course. They should have gotten a brief introduction to MATLAB in the course "Introduction to Engineering" when they first entered the degree program. However, for a transfer student who skipped the course, he/she might have no prior experience with MATLAB. Because of students' different MATLAB abilities, significant scaffolding was given in the labs. MATLAB tutorials along with tutorials on the subject areas were provided. Students were also given a partially completed MATLAB script for each lab with detailed comments describing the purpose of each MATLAB command.

To engage students' interest, all labs were written using story telling through a fictional character Bob, who was a friend and a fellow student. He asked students in the class to help him solve problems that require knowledge of signals and systems. The five labs are described in details next.

A. *Lab 1: Let's Make Music*

This lab introduced students to the first application area of signals and systems, signal processing. The focus of the first lab was time domain signal transformation. The lab intended to use an audio signal as an example to demonstrate the effect of time domain signal manipulations such as time scaling, time reversal and magnitude scaling.

In the lab, Bob asked students to make and play a piece of music and implement common audio editing functions such as speeding up, slowing down, fading in, fading out and playing in reverse. Students learned how to use MATLAB and sampling theorem to generate and play digital audio signals (music notes in this case). They also learned how to transform signals in the time domain.

B. *Lab 2: Opera in Italy, Anyone?*

Many students had trouble understanding the concept of impulse response and convolution. This lab tried to manifest the meanings of a system, its input, output and impulse response in a real world scenario. Specifically, reverberation was used as an example to illustrate the concepts. The lab was based on the following theory. Audio characteristics of a performance space (system) is captured in its impulse response. Given an audio (system) input, convolution can be used to generate the audio (system) output. By capturing the impulse responses of different performance spaces, the reverberation effect of those spaces can be experienced without the listener being physically present in the spaces. This example clearly demonstrated the value of capturing the system characteristics in its impulse response and using convolution to simulate the system output.

In lab 2, Bob presented students with a short recording of an opera singer in a sound proof room. He wanted to hear how his recording would sound in spaces with different acoustic characteristics, such as the Milan Opera House in Italy, the St Nicolas Church in Prague and the Grand Canyon. Students were given a primer on reverberation. They then learned how to convolve an input signal with an impulse response to determine the output signal. They were provided with the impulse responses of the above mentioned spaces. Through signal convolution, they could hear the output after the recording passed through those spaces (systems) with different reverberation effects, as if they were there themselves.

C. *Lab 3: Get Rid of That Noise Please*

This lab intended to make students take the leap from analyzing signals in the time domain to the frequency domain. Fourier analysis is an important tool in signal processing but can be difficult for some students to comprehend.

The lab started with a short tutorial on Fourier analysis and filter basics. Before jumping into a real world (often messier) example right away, students first analyzed the song they created in Lab 1. Through an example of how to compute and plot Fast Fourier Transform (FFT) in MATLAB, students could visualize the FFT frequency peaks of the song. They found the peaks indeed corresponded to the note frequencies they generated in Lab 1, thus making the connection between time domain and frequency domain. Next Bob gave students a music file corrupted by background noise. He asked for students' help to remove the noise and restore the music piece. An example of how to build a digital filter in MATLAB was provided. Students were asked to choose an appropriate cutoff frequency for the low pass filter to filter out the noise.

D. *Lab 4: Turn on Cruise Control*

Control is a good application area for students to see how the Laplace transform, the system transfer function and stability are used in practice. Due to time constraints, control systems are not explicitly covered in the course beyond basic feedback calculations. But it was decided to include the topic in a lab exercise to give students some exposure to the subject area, which is an important application of concepts in the signals and systems.

In the lab, students were given a brief overview of control systems and PI controllers. A simplistic model of a cruise control system was also provided [14]. Students were asked to derive the system transfer function of the feedback controller. Bob then asked students to help him design a cruise control system for his Toyota Corolla to satisfy certain performance metrics such as acceleration speed and not going over speed limit, etc. Specifically, students needed to tune the parameters of the PI controller to meet the design requirements.

Ideally, to make the connection between theory and practice, students would benefit more from building a hardware implementation of a simple control system. With the simulation lab, students at least learned the terminology of a control system and had a first-hand experience on how changing the parameters of a controller could impact system stability and parameters such as rise time, settling time, overshoot etc.

E. Lab 5: What for Lunch?

The Fourier transform multiplication property was a difficult concept for students to grasp. No application is better at illustrating this concept than modulation. It also serves as a good introduction to another important application area of signals and systems: communication systems.

In this last lab, students first worked through a tutorial on amplitude modulation. They were asked to derive the Fourier transform of the signals after modulation and again after demodulation by applying the multiplication property. Then they read the code of the MATLAB amplitude demodulation function and described how a signal was restored after demodulation.

Bob posed his final challenge by modulating an audio message using amplitude modulation. The message was an audio recording of Bob reading a lunch menu. Students were given the modulated message and they needed to demodulate the message to decode the lunch menu. Besides learning how to modulate/demodulate, students also learned how to properly up-sample and down-sample during the modulation and demodulation process to satisfy the Nyquist Theorem.

IV. Assessment and Results

The MATLAB labs were incorporated in the course and piloted in the fall semester of 2017 with 36 students enrolled. The labs were then improved upon based on student feedback and reoffered in the spring semester of 2018 with 44 students enrolled.

Among the students from the two sections of Signals and Systems I in the fall of 2017 and in the spring of 2018, a total of 41 students consented to participate in the survey approved by the Institutional Review Board (IRB). The survey was given to the students at the end of the semester. The survey questions are shown in Table III. The survey had seven questions using a 5-option symmetric disagree-agree scale. A score from one to five was assigned to each point on the disagree-agree scale with one being "strongly disagree" and five being "strongly agree". The eighth question was a free response question asking students for their overall experience and suggestions for improvement.

TABLE III. Survey Questions

Number	Questions
1	The "Make Music" lab helps me understand the concepts of sampling and signal manipulation in the time domain.
2	The "Reverberation" lab helps me understand the concepts of system impulse response and convolution.
3	The "Noise Removal" lab helps me understand the concepts of Fourier analysis and digital filter.
4	The "Cruise Control" lab helps me understand the concepts of system transfer function and Laplace transform.
5	The "Modulation" lab helps me understand the concepts of amplitude modulation and demodulation.
6	The five MATLAB labs help me connect abstract theoretical concepts with real world applications.
7	The five MATLAB labs help me apply signal and system concepts to solve real world problems through MATLAB programming.
8	What is your overall experience with the MATLAB labs? What worked for you? What didn't work for you? What improvement can you suggest? Any additional comments?

A. Survey Scores

Students' response to the seven Likert scale questions are shown in Fig. 1. The figure shows the average score of each survey question for the Fall 17 and Spring 18 semesters. It also shows the average of the two semesters.

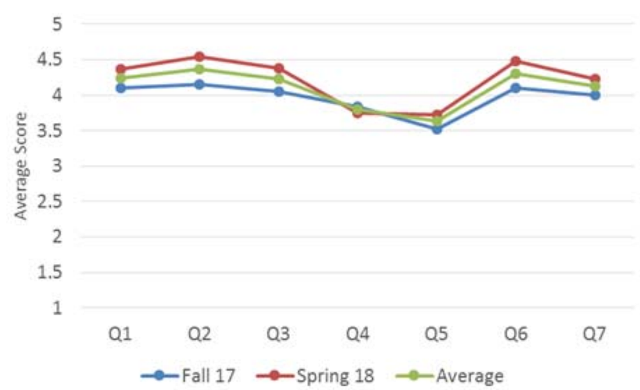

Fig. 1. Average score of student responses to survey questions 1 through 7 (with strongly agree as 5 and strongly disagree as 1)

The result in the figure shows that students had positive experience with the labs. The modifications made after the first offering also improved students' experience during the second offering.

Students responded to the five labs differently. Lab 1, 2 and 3 had average ratings of 4.2, 4.4 and 4.2, while Lab 4 and 5 got 3.8 and 3.6. From students' responses to survey question 9, one can get a glimpse of the reasons behind those ratings. Students felt that Lab 1 through 3 were better in-line with the course content. Lab 4, the simulation of a simple control system, was not very real world. Lab 5, the modulation lab, was too complex and took way more time to complete than the other labs. To make things worse, Lab 5 was assigned during the last week of class when students also had to study for the final exam.

Question 6 and 7 got average scores of 4.3 and 4.1. They showed that students did feel that the labs helped them connect abstract concepts with real world application and helped them apply the concepts learned to solve real world problems.

To study how these labs affected students with different abilities, scores were averaged across the seven Likert scale questions for each student, and they were plotted against their final total grade percentile in the class. The result is shown in Fig. 2. The figure shows there is no strong correlation between student survey score and their standing in the class. In other words, the labs were perceived positively by students with all abilities.

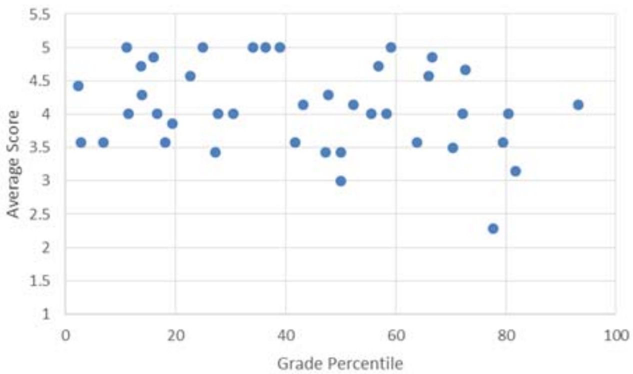

Fig. 2. Average Survey Score v.s. Final Grade Percentile

B. Student Comments

The overall impact of the MATLAB labs can be best described using students' own words, from their comments in survey question 9, which are in quotation marks below.

Overall students felt they had a "quality lab experience." One said "I enjoyed working the labs, the application was quite interesting," another said "The MATLAB was the best part of this course," yet another said "I looked forward to the MATLABs each week."

Many mentioned they "didn't know MATLAB very well" and had difficulty with MATLAB coding sometimes. They appreciated how a considerable portion of the working code was provided, thus allowing them to focus only on the central task or goal, rather than having to "fight" with MATLAB to get it to do what they needed. "These labs did a very good job of using MATLAB as a tool instead of teaching MATLAB. This helps the student gain the understanding of the concept instead of using most of their time trying to complete a lab because that don't know how to code in MATLAB." However, the downside to the scaffolding was that "I (they) cannot say with complete certainty that I (they) would be able to reproduce similar MATLAB experiments on my (their) own." Probably this was the reason why survey question 7 received less score than question 6.

The labs helped students "understand the course materials" and "solidify the concepts of the class." "They pieced together why we (they) were doing the homework and made sense." "They had expanded my (his/her) understanding of the concepts of this course in a way that the homework assignments, quizzes, and exams could not." "By utilizing the plots in MATLABs and writing the script, it was much easier to visually connect the concepts in class with real-life concepts."

The goal of connecting theory to practice seemed to have been accomplished as well. Many liked the lab setup and the storytelling. "They posed interesting, real-world hypotheticals and allowed us (them) to really get in and try out various functions in an enjoyable way." Students felt "the MATLAB labs were fun and allowed me (him/her) to see the real world applications," "they did a fantastic job at showing that these concepts are able to be applied in the real world," and "they gave a great connection to the material and allowed for a better understanding of real situations in which the material could be used."

Specifically, "The MATLAB labs helped me (him/her) somewhat understand why I'm (he/she is) analyzing signals, or at least what signal analysis can accomplish when used." "The lunch signal modulation and the cruise control labs were geared toward understanding where you (one) can apply the tools learned in class to a project, and from that point I (he/she) understood a decent amount more of the amplitude demodulation/modulation and system transfer function and Laplace transform."

Students saw "exercises like these are essential for making a heavily theoretical class more interesting. Anything that will help me (him/her) to solidify theory through practice is extremely helpful." "Without the labs, this course would have been just another math class with very little understanding of how the concepts can be applied in the real world."

It was good to see these application examples motivated one student to choose his EE focus area: "I really enjoyed the labs overall. In fact, this class has helped me determine what my focus in electrical engineering will be moving forward in my studies."

It was interesting to see that even Lab 5 received the lowest rating out of the five labs. There were a few students enjoyed it the most. "The last lab dealing with amplitude modulation and demodulation was by far the best one. It required quite a bit more thought than the others and it really drove home the math and reasoning behind it."

There were a few negative comments. Some students were struggling with MATLAB and felt that "it was hard to meld together the coding aspects of MATLAB with the conceptual learning of the course."

There were also complaints regarding work load and time commitment. One commented, "The (course) concepts are quite difficult to grasp that for me it would be a lot easier if I didn't have to worry about having a lab due on top of everything." Another said, "Instead of time studying and learning the material even better I had to just power through these labs losing critical time."

There was also a comment due to a student wanting more from the lab: "With regards to the lab, the only reason I gave a lab a poor rating was because I feel I could do more with the lab. For example, the cruise control lab was frustrating because it was a guess and check and I never really got the system to work appropriately and really wanted to. The lunch (modulation) lab was really cool, I feel I need much more information on modulation however. With all that in mind though, I think the labs were intended to make a connection from our theoretical studies to actual real world applications. If that is in fact the case, the labs were a huge success. I just really wanted to learn more about the labs and maybe even write my own code."

C. Exam Scores

Exam scores from these two terms were also compared against scores from previous terms. No noticeable differences were found. This was expected since the MATLAB lab exercises were not intended to help students with their mathematical manipulations of theoretical equations, which were the focus of exam questions.

What students gained from the labs, which wasn't assessed by exams, was that "they expanded my (his/her) understanding of the concepts of this course in a way that the homework assignments, quizzes, and exams could not", "helped me (him/her) somewhat understand why I'm (he/she is) analyzing signals, or at least what signal analysis can accomplish when used" and "make a connection from our (their) theoretical studies to actual real world applications."

V. Future Work

Students' suggestion for improvement included making the lab instructions clearer and more explicit. They also wanted more explanation on what MATLAB functions in the scripts did and why they were used, especially in the already provided code skeleton. These would help them see a full picture of the application. They also suggested creating more labs and assigning less homework, because "I (He/She) gained a greater understanding of the course material from the labs than I (he/she) ever did from the lectures, text, or homework." In addition, the schedule could be adjusted. Lab 1 through 5 could be offered in Week 1, 2, 4, 6 and 5 instead of the current schedule, thus avoiding having the difficult Lab 5 during the last week of class. These will be the focus areas in the next rounds of improvement and lab offerings. Finally, after seeing the success of these MATLAB labs in the online version of the course, they will be offered in the face-to-face version as well.

VI. Conclusion

Five MATLAB hands-on lab exercises were implemented in an online introductory signals and systems course. Survey results showed that most students, regardless of course performance, enjoyed the labs. They acknowledged that the labs helped them solidify theory through practice and also helped them connect and apply signals and systems concepts to real world applications. Future work includes further lab improvements, development of more labs and offering the labs in the face-to-face course.

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