Improving Conceptual Understanding of Signals and Systems in Undergraduate Engineering Students Using Collaborative In-Class Laboratory Exercises

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Abstract

Three MATLAB-based in-class collaborative laboratory exercises were introduced in conjunction with the traditional lecturing and problem-solving techniques in the signals and systems course at Vanderbilt University. These labs were developed to enhance students' conceptual understanding and retention using MATLAB simulations of audio synthesis and processing, using guitar notes as signals and processing these signals through linear time-invariant (LTI) systems to produce sound effects. The impact of the new curriculum on students' conceptual understanding was evaluated through three techniques – quantitative assessment using the Signals and Systems Concept Inventory (SSCI), and qualitative assessment using a voluntary end-of-semester lab survey and a small group analysis. Analysis of SSCI scores from the first batch of students in the new curriculum indicated a course average normalized gain of 0.54 in the discrete time SSCI and 0.61 in the continuous time SSCI student performance. Student agreement on the labs (reinforcing the concepts of signal transforms and visualization, convolution and filtering) correlated well to their actual SSCI scores on questions based on these concepts. Analysis of subtest topics suggested persistence of common misconceptions, thereby motivating suitable changes to the lab exercises to be implemented in future semesters. Student performance and responses indicated that the collaborative laboratory exercises improved student learning and also suggested areas for improvement in the lab exercises for future semesters.

Introduction

The undergraduate electrical engineering program at Vanderbilt University offers an introductory signals and systems course (EECE 214: Signals and Systems) focusing on continuous and discrete time signals and systems representations and analyses. Sophomore and junior level electrical, computer and biomedical engineering students with the required prerequisites of Electric Circuits, Calculus and a basic programming course (MATLAB/C++/JAVA) take EECE 214 to acquire a strong foundation for advanced courses such as digital signal and image processing, biomedical signal processing and control systems. Traditionally, classroom lecturing and problem-solving sessions with MATLAB-based demos of practical applications have been the preferred teaching technique in this course, with a goal of emphasizing the interdependence of mathematical representations and tangible physical interpretations of concepts. Targeting this level of conceptual understanding in students has been a persisting challenge to instructors[1, 2]. Towards this end, MATLAB/LabVIEW based software simulations[3, 4, 5] and analog circuits based hardware lab exercises[6, 7] have been developed and implemented successfully in several universities with significant improvement in students' conceptual understanding of signals and systems. Based on these existing lab curricula, three in-class MATLAB-based collaborative lab exercises were developed and implemented in the EECE 214 course curriculum in fall 2013. This paper outlines the significance and features of these lab exercises, their impact on students' conceptual understanding as assessed by the SSCI and student feedback, and persisting student misconceptions that may be effectively addressed by modifying the lab exercises.

EECE 214 introduces time and frequency domain representations and analyses of continuous and discrete time signals and LTI systems. New concepts such as convolution, LTI system theory, sampling, Fourier analysis and, Laplace and Z transforms are presented through lectures and problem-solving sessions. Students can exhibit inabilities to apply the following learning skills required in this course - (a) integration of their prior knowledge of calculus and complex numbers to develop a strong mathematical foundation of these concepts with a thorough understanding of the computational procedures involved, (b) graphical interpretation of the mathematical basis of these concepts to understand their physical meaning and hierarchical relevance in the course curriculum and, (c) successful application of these concepts with appropriate mathematical formulations to solve practical problems on signal filtering, modulation and optimal system design. Previous research[1] indicates many students find skills (a) and (b) challenging, specifically with concepts of convolution and Fourier transforms, thereby resulting in the inability to solve practical problems and learn advanced topics.

Based on the success of MATLAB-based lab exercises as part of the signals and systems curriculum in many universities[8, 9, 10, 11], the instructors at Vanderbilt University developed three in-class collaborative MATLAB-based lab exercises that were included in the existing EECE 214 curriculum. Software simulation tools such as MATLAB can facilitate step-by-step visualization of computational procedures and their results while solving signals and systems problems. A broad spectrum of problems ranging from simple mathematical computations in convolution or frequency domain transforms to application-based system design of filters and feedback systems can be effectively simulated using MATLAB. MATLAB-based homework problem sets in EECE 214 target the mathematical problem-solving component and the in-class labs focus on reinforcing concepts through application-based practical problem solving.

The new curriculum with the in-class labs and problem sets was implemented in the fall 2013 semester with an enrollment of 19 students (18 electrical and computer engineering sophomores and juniors and one biomedical engineering junior). Since MATLAB programming was not an explicit prerequisite for this course, an initial class survey indicated over 50% of the students were inexperienced MATLAB programmers. These students were encouraged to utilize the multiple MATLAB tutorial sessions conducted by the teaching assistant. Since the primary goal of the course was to utilize MATLAB as a tool to reinforce concepts and provide a platform for hands-on simulation and modeling of signals and systems, the MATLAB code for the lab exercises was provided to the students. In addition to interpreting the results of the lab exercises in terms of relevant concepts, the technical lab report focused on code interpretation and execution, and user input parameter variation, thereby providing moderate training in MATLAB programming.

The three in-class labs replaced three lecture sessions suitably to ensure continuity in the lecture content. In addition to a brief introduction of the labs in the prior lecture session, students were provided with pre-lab exercises that were to be reviewed before the in-class lab session. The pre-lab module introduced key concepts reinforced in the lab and suggested additional resources (online review articles and tutorials) relevant to the application of these concepts. The in-class lab module comprised of short MATLAB exercises implementing and testing one or more concepts. The in-class lab sessions foster collaborative learning among the students by having them work in randomly assigned small groups. The lab sessions began with the instructor giving an overview of the exercises and the corresponding MATLAB code, and providing relevant block diagrams of systems, expected graphical outputs, and suggestions for user inputs to simulate various system behaviors. This introduction was followed by group work with instructor assistance as needed, thereby stimulating peer and instructor interaction. Each MATLAB exercise consisted of guided questions that helped students associate the MATLAB implementations with the underlying concepts and develop a qualitative and quantitative interpretation of the observed outputs. The final component of the in-class labs was the collaborative technical lab report with students' answers to the pre-lab and in-lab questions and brief interpretation of the MATLAB code in terms of the concepts implemented and challenges encountered with its execution while simulating various system behaviors.

Laboratory Exercises

Audio signal synthesis and processing is a standard application that has been utilized successfully in several MATLAB-based signals and systems lab curricula[4, 8, 9]. The three in-class labs in EECE 214 are also based on this application with the goal of improving students' conceptual understanding of signals and systems. Table 1 describes the applications and concepts targeted in the three in-class lab exercises.

Week in Semester	Applications	Tasks	Concepts
Lab 1 – Week 6 (Modeling guitar music)	• Frequency of music notes • Guitar harmonics on a vibrating string • Chords and tunes • Guitar strumming effect	• Play music notes (4s sine wave) at fundamental frequency • Model open and fretted string guitar notes on a vibrating string using Karplus Strong algorithm • Model and play B minor chord and compare to actual guitar notes • Model and play 'Hot cross buns' • Create strumming effect on B minor with delay of 50ms between notes of the chord	• Modeling guitar notes as LTI system (Karplus Strong algorithm - low pass filter and a delay line) • Convolution of unit impulse function with impulse response of LTI system. • Time and frequency domain representations of exponentially decaying sinusoids to observe interaction of fundamental frequency and harmonics using Bode plots and spectrograms

Table 1: Laboratory Exercises

Week in Semester	**Applications**	**Tasks**	**Concepts**
Lab 2 – Week 12 (Modeling audio effects)	• Design Equalizer to create high cut, low cut, bandpass, and, bandstop effects • Create phasing, chorus and echo audio effects	• Design 8th order low pass, high pass, bandpass and bandstop Butterworth filters to simulate equalizer effects (filtering) on guitar notes. • Design feed forward (FIR) comb filter with unity gain and variable delay lengths to simulate phasing (5 ms), chorus (50 ms) and echo (150 ms) effects on guitar notes. • Design feedback (IIR) comb filter with unity gain and delay length of 150 ms to simulate unstable echo effect.	• Guitar notes as LTI systems • Filtering (order, cut off frequency, gain, roll-off, pass band ripple) • Cascading LTI systems – LTI and Convolution properties • Time and frequency domain representations of input (guitar notes), filter impulse response and output (filtered, phasing, chorus, echo effects on guitar notes) using Bode plots, pole zero plots (system stability and causality), and spectrograms
Lab 3 – Week 16 (Room acoustics, sampling and denoising)	• Concert hall reverberation of pre-recorded guitar music • Removing high frequency microphone feedback • Effects of over and under-sampling of voice signals	• Simulate Schroeder reverberator using comb and allpass filters and compare to pre-recorded concert hall impulse response. • Simulate reverberations using Schroeder and pre-recorded room impulse response • Simulate high frequency microphone feed back added to guitar music. • Design notch and low pass filters to filter high frequency microphone feedback • Resampling students' voice signals above and below Nyquist rate.	• Cascading LTI systems (LTI and Convolution properties) • Time and frequency domain representations of input (guitar music), Schroeder impulse response, and output (reverberating guitar music)- Bode plots, pole zero plots (system stability and causality), and spectrograms • Filtering(order, cut off frequency, gain, roll-off, pass band ripple) • Nyquist criteria, upsampling, downsampling, interpolation, and aliasing effects.

Table 1: Laboratory Exercises (contd.)

The student-instructor and within-group student interaction was significant in the in-class lab sessions with greater emphasis on conceptual learning than on MATLAB execution to arrive at the correct solution. An example of guided questions from one of the lab exercises is shown in Figure 1.

> **Exercise 2:** Run Lab2_2.m to apply the above Butterworth filters to the guitar open A string. You are given pluckguitar.m to generate guitar A note (**how is this different from openstring.m in Lab 1?**). Open string A was generated using a LTI system and the Butterworth filter is an LTI system. This is an example of cascaded LTI systems, where the output of the first system is convolved with the impulse response of the second system. *Remember the properties of convolution?*
>
> Compare the frequency spectra and pole-zero plots of the high cut, low cut, bandpass and bandstop equalizer effects on openstring A. Discuss in terms of filter order, roll-off, pass band ripple and transition band.
>
> - Correlate the quality of the sound to the corresponding frequency spectrum.
> - Test the high-cut effect with different orders. Compare the quality of the sound and the frequency spectra (Bode plots/plot-zero plots and spectrogram).

Figure 1 Example of guided questions from Lab 2

Assessment Methods

The technical lab reports do not test conceptual understanding directly given the subjectivity in interpreting simulation results. Hence three types of assessment methods have been used to quantitatively and qualitatively evaluate the students' conceptual understanding of signals and systems in the new curriculum. This study was approved by the Vanderbilt Institutional Review Board.

The SSCI is a widely used tool[3, 6, 13, 14] to quantify conceptual understanding of signals and systems. It consists of a continuous time (CTSSCI) and a discrete time section (DTSSCI) each with 25 multiple choice questions[12]. These questions test concepts directly with little or no computational requirement. Each exam is comprised of subtests in the following signals and systems topics – background mathematics, convolution, LTI systems, filtering, transforms, and sampling (only in DTSSCI). Some questions may involve the synthesis of two or more topics. Since EECE 214 comprises of both continuous and discrete time signals and systems, students completed both the CTSSCI and the DTSSCI questionnaire in the same session. A pre-course SSCI session was conducted in the third week of classes after the introduction of sampling and convolution and a post-course SSCI session was conducted as part of the course final exam. The latest versions of the CTSSCI (v5.0) and DTSSCI (v5.1) were used in the study. Table 2 shows the list of concepts tested in each of the questionnaires.

Qualitative assessment of the impact of the labs on students' conceptual understanding was performed using a voluntary end of semester lab survey and a small group analysis; both designed to gather student feedback on the new curriculum.

Question	**CTSSCI**	**DTSSCI**
1	Math	Math
2	Math	Math
3	Math	Math
4	Math	Math
5	LTI	Math
6	Trans/Filt	LTI
7	Trans	Sampling
8	LTI	Sampling
9	Trans	Trans/Filt
10	Trans	Trans
11	Trans	LTI
12	Trans	Trans
13	Conv	Trans
14	Conv	Trans
15	Conv	Conv
16	LTI	Conv
17	Trans	Conv
18	Trans	LTI
19	Trans	Trans
20	Trans	Trans
21	Conv/Trans	Trans
22	Trans	Trans
23	LTI/Conv	LTI/Conv
24	LTI	LTI
25	Trans/Filt	Trans/Filt

Table 2 List of concepts in the CTSSCI and DTSSCI (Conv – convolution, Trans – transform, Filt- filtering). Transforms include Fourier, Laplace, and Z transforms.

The end of semester lab survey comprised nine questions as seen in Table 3. Ten EECE 214 students completed the voluntary survey. Student responses to question 1 were compared to their actual SSCI scores to observe if they indicated a strong correlation confirming the impact of the labs on students' conceptual understanding. The other questions were used to determine overall student response to the MATLAB-based labs with the goal of further improving them.

The small group analysis was an anonymous group survey conducted by a Vanderbilt University Center for Teaching (CFT) consultant[15]. Students organized into small groups completed a questionnaire comprising the following questions –

1) Quickly identify what your group sees as the primary learning objective of the course.
2) What aspects of this course and/or the instruction would you identify as most helpful to your learning?
3) How are these aspects helping you to learn in this course?

4) What modifications to this course do you believe would help you to learn more effectively? Why do you believe these changes would improve your learning?

Qn #	Name
1	Which of the following concepts did the labs help you understand better?
2	Did you understand the mathematical basis of MATLAB codes relative to the concepts learned in class?
3	Was it helpful to have the MATLAB code available for this lab?
4	How well did the labs relate to the lectures?
5	Which of the following areas did the labs help you with?
6	If given a pseudo code, will you be able to develop the MATLAB code for the same?
7	Did the in-class Labs help in overall conceptual understanding of the course?
8	Which of the following topics are you most confident about having taken EE 214
9	Suggestions/Comments to improve Labs to better understand Signals and Systems

Table 3 End of semester lab survey

The consultant then led a large group discussion based on the student responses further probing into areas of agreement and disagreement among the students. A consolidated report of the small group responses and the large group discussion was provided as student feedback to the instructor. The student responses pertaining to the lab exercises will be discussed in the results section, indicating the utility of the labs in reinforcing signals and systems concepts.

Assessment Results

SSCI Performance

The SSCI performance was evaluated at two levels – overall SSCI performance and performance on subtest topics. Richard Hake[16] defined normalized gain measures of student performance by comparing pre-course and post-course test scores to evaluate post-instruction student performance on the Force Concept Inventory (FCI). He defined single student normalized gain as $g = (\% \text{ post} - \% \text{ pre}) / (100 - \% \text{ pre})$, where % post and % pre refers to the student's post-course and pre-course test scores expressed in percentages. The course average normalized gain is defined as $\langle g \rangle = (\langle \% \text{ post} \rangle - \langle \% \text{ pre} \rangle) / (100 - \langle \% \text{ pre} \rangle)$, where <% post> and <% pre> refers to the class average post-course and pre-course test scores expressed in percentages. In Hake's survey[17] of over 6000 physics students taking the FCI, he reported that <g> for classes with only traditional teaching techniques was 0.23 ± 0.04, and <g> for classes employing interactive engagement techniques was 0.48 ± 0.14. The collaborative in-class labs in EECE 214 employ interactive engagement techniques with peer and instructor collaboration thereby providing immediate feedback to target misconceptions. Hake's normalized gains have been widely used in previous research[6], including the development of the SSCI[12].

This study uses the single student normalized gain 'g' and the course average normalized gain '<g>' as measures of overall performance on the SSCI based on the pre-course and post-course SSCI scores. Table 4 lists the single student and the course average normalized gain of the 19 students in EECE 214.

Single Student Normalized Gain		
Student	DTSSCI	CTSSCI
1	-0.50	0.57
2	0.70	0.83
3	0.63	0.71
4	0.86	0.60
5	0.67	0.67
6	0.35	0.15
7	0.45	0.25
8	0.40	0.67
9	0.44	0.77
10	0.14	0.56
11	0.79	0.91
12	0.36	0.30
13	0.73	0.70
14	0.50	0.33
15	0.56	0.64
16	0.50	0.87
17	0.31	0.18
18	0.85	0.82
19	0.64	0.77
Course Average Normalized Gain		
DTSSCI		0.54
CTSSCI		0.61

Table 4 Normalized gains

The second level of analysis on the SSCI scores was performed by comparing the class average pre-course and post-course SSCI scores obtained in each subtest. The subtests were categorized as seen in Table 2 based on the topics of background mathematics, convolution, LTI systems, sampling (only in DTSSCI), transforms (including Fourier, Laplace, and Z) and filtering. Figure 2 shows the pre- and post-course class performance in each of the subtests as compared to the maximum subtest score possible in that subtest. A significant increase in the subtest scores was observed in every subtest topic except the background mathematics questions. Question 3 in the CTSSCI and questions 3 and 5 in DTSSCI described below, contributed to the small decrease in class average on the background mathematics subtest scores.

Question 3 (CTSSCI): Time shifting of signals, given r(t), identify r(2-t)
Question 3 (DTSSCI): Time shifting of signals, given r(n), identify r(2-n)
Question 5 (DTSSCI): Periodicity of signals, given Cos($w_o n$), identify Cos(($w_o n + 2\pi$)n)

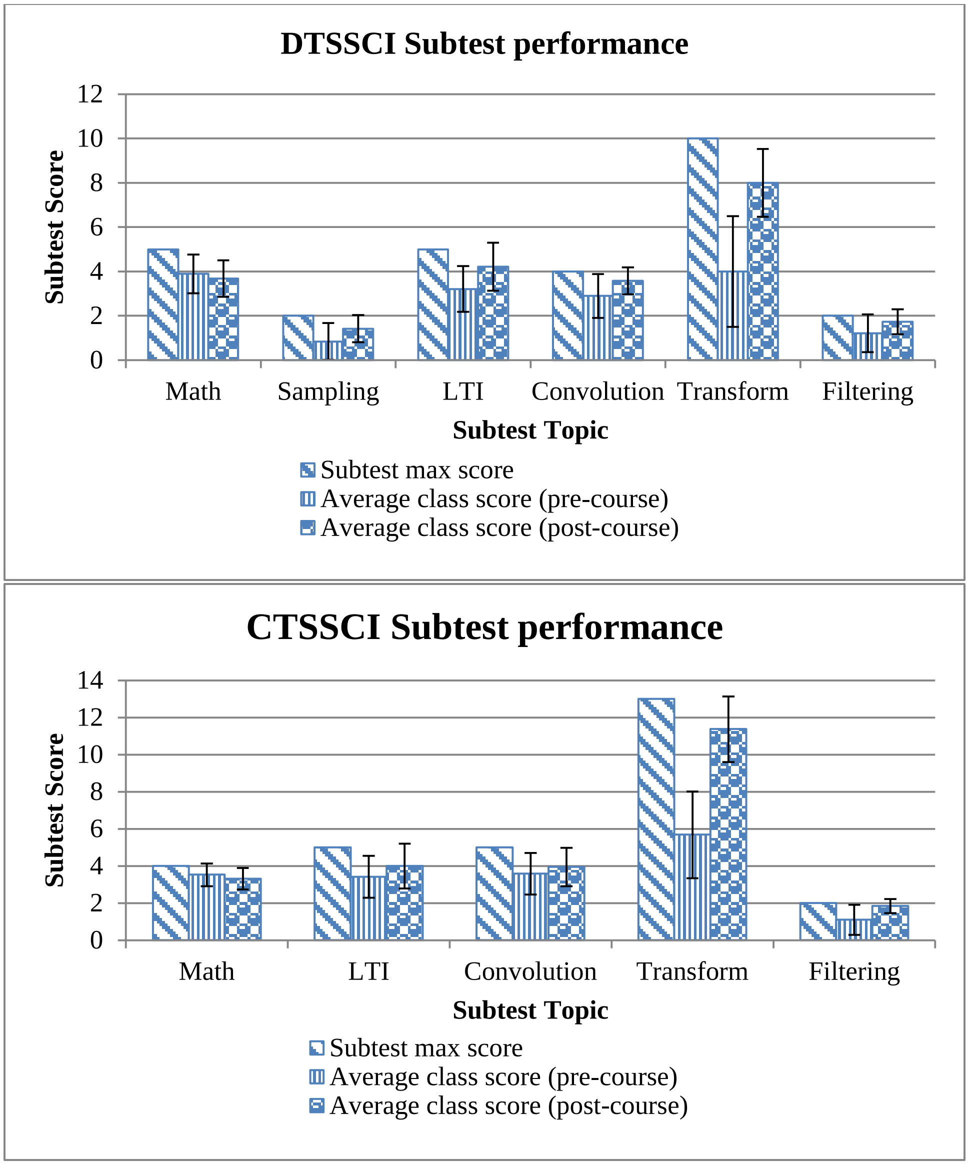

Figure 2 Class average scores on SSCI subtests

Lab Survey

The voluntary lab survey was completed at the end of the semester by ten EECE 214 students and responses are presented in Table 5. The responses to question 1 listed the topics that the student perceived as concepts reinforced through the lab exercises. The top half of Table 5 compares the percentage of students who had indicated that a specific concept was reinforced by the lab exercises and the percentage of students who had obtained atleast 80% on the post-course CTSSCI and DTSSCI questionnaires. For example, seven out of ten students reported that the lab exercises reinforced the concept of sampling. Four out of these seven students scored over 80% in the DTSSCI subtest on sampling.

The lower half of Table 5 indicates student responses on the subjective questions (#2 - #7). The percentages in parenthesis indicate the percentage of students giving that specific response to the questions.

Concepts	% of students (out of 10 students)	% of students with at least 80% subtest score (based on % of students who chose the concept)
Sampling	70	40
LTI	10	0
Convolution	30	20
Transform	80	80
Filtering	100	90

Lab survey Questions 2 - 7	Responses from 10 students			
Did you understand the mathematical basis of MATLAB codes relative to the concepts learned in class?	Partially (100%)			
Was it helpful to have the MATLAB code available for this lab?	Yes (90%)	No (10%)		
How well did the labs relate to the lectures?	Partially (90%)			
Which of the following areas did the labs help you with?	Details (40%)	Big picture (70%)	MATLAB is useful (70%)	
If given a pseudocode, will you be able to develop the MATLAB code for the same?	Yes (20%)	Prefer code (40%)	Willing to try (30%)	No (10%)
Did the in-class Labs help in overall conceptual understanding of the course?	Agree (80%)	Agree strongly (10%)	No effect (10%)	

Table 5 Lab survey responses from 10 EECE 214 Students (top – Question 1, bottom – questions 2 – 7)

Small group analysis

The responses from the small group analysis pertaining to the lab sessions indicated that the students generally agree that the in-class labs emphasizing the applications of signals and systems were helpful in visualizing and reinforcing concepts. Few student responses on the small group questionnaire are quoted below

- "The in-class labs help us visualize what is going on."
- "The in-class labs are helpful to understand the material."
- "The MATLAB exercises and the in-class labs are good for understanding concepts and applications."

These responses were consistent with the voluntary lab survey responses seen above.

Discussion

Three collaborative MATLAB-based in-class labs were introduced in the signals and system course and its impact on students' conceptual understanding of the subject was evaluated. The labs were designed to enhance students' ability to understand and integrate individual concepts and apply them successfully in practical applications such as audio synthesis and processing.. Despite the existence of NI ELVIS, LabVIEW and Java-based tools for signals and systems laboratory courses, MATLAB continues to be the most widely used tool in core and advanced level signal and image processing courses. Hence, MATLAB was the preferred tool used to implement and test the lab exercises in EECE 214. The results based on the three assessment techniques indicate a positive impact of the labs on students' conceptual understanding of signals and systems. Except for one student with a negative gain on the DTSSCI, all students contribute to a high course average normalized gain of 0.54 on the DTSSCI and 0.61 on CTSSCI. These gains were found to be consistent with the range of course average normalized gains reported by Hake in classrooms employing interactive engagement techniques[17]. Previous research employing a subset of questions from the CTSSCI as a tool to assess impact of hardware labs on students' learning of signals and systems have reported course average normalized gains of 0.3 in the first year and 0.54 in the second year of implementation[6], which are comparable to the gains obtained in this study.

Even though the pre-course questionnaires were administered in the third week of classes after the introduction of convolution and sampling, there was an increase, albeit small, in post-course scores on these topics indicating that the baseline performance on the pre-course questionnaire was moderately similar to the expected baseline performance if the questionnaire were administered in the first week of classes. The pre-course questionnaires in the future semesters will be administered on the first day of classes to achieve more accurate student baseline performance.

The analysis of the SSCI scores on each of the subtest topics was insightful in determining the areas of difficulty and the persistence of misconceptions towards the end of the course. An interesting observation was the decreased score observed in the background mathematics subtest, specifically testing time shifting properties and periodicity of signals. An average of 54% of the class continued to apply the time shifting concept incorrectly while flipping and advancing the signals. Similarly, the periodicity of a cosine wave being 2π was misinterpreted as a two fold increase in the frequency of the waveform. These low scores on background concepts indicate a possible inability to visualize and simplify a specific problem as opposed to using a generic set of procedures while solving them. These results indicate the need for a stronger foundation on these background questions in the prerequisite courses and their review in EECE 214. The labs did not specifically target these background concepts and it would be advantageous to include them in the Lab 1 pre-lab module in the future semesters.

Fourier, Laplace and Z transforms and filter theory are introduced for the first time in EECE 214. These subtest scores indicated the highest increase in the post-course performance in the DTSSCI and the CTSSCI questionnaires, suggesting an improved conceptual understanding in these topics. As seen from Table 1, all the three labs focused extensively on transforms, their representation and filter theory and atleast 80% of the students who took the lab survey indicated that the labs successfully reinforced these concepts.

The small group analysis and voluntary lab survey indicated the positive reception of the lab into the curriculum. Nine out of ten students who completed the lab survey indicated that the labs were effective in improving the overall conceptual understanding of the subject and reasonably related to the lectures. All ten students responded positively that MATLAB was moderately useful in relating the mathematical basis of the concepts. The instructors propose to improve this by providing MATLAB pseudo code for the second and third labs, which can lead to greater student involvement in the implementation of concepts and linking them through various functions to design and test a complete system such as the Schroeder reverberator or the equalizer. The hands-on programming experience can aid in better understanding of the computational steps involved in the solution. Feedback from the small group analysis distinctly indicated student satisfaction and enthusiasm towards the labs in improving learning, but also expressed the need for a more cohesive presentation of the lectures, labs and the assignments. Future semesters will focus on better integration of these three aspects of the course by emphasizing the significance of mathematical basis of the concepts and their practical applications simultaneously in the labs. This integration can be achieved by modifying the pre-labs suitably to include computation based questions such as obtaining transfer functions of systems and calculating their Fourier or Laplace transforms.

The new curriculum with modifications to the in-class labs to include basic mathematical concepts, mathematical computations, and pseudo codes will be implemented in the future semesters with similar assessment techniques. The SSCI questionnaires will also be administered to the fall 2013 students in end of the spring 2014 semester to test the impact of the labs on retention of concepts after a period of one semester. Thus, the findings from our study indicate the successful implementation of in-class lab sessions in the signals and systems curriculum meeting the goal of improving students' conceptual understanding. This study also serves to reinforce the significance of practical laboratory exercises emphasized by previous studies, thereby contributing to the development of good educational practices.

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