WIP: Knowledge Integration to Understand Why

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1. Introduction

Mastering key concepts within electrical engineering often involves students taking courses in electronics, signals and systems, and electromagnetics. These courses are typically taught during the middle two years of an electrical engineering program where these courses are often taught in parallel during semesters, however, typically few interactions occur among them. Consequently, students learn key concepts in isolation, whereas by connecting key concepts in electronics, signals and systems, and electromagnetics through a set of known applications allows students to integrate key concepts from a utility standpoint. Such a learning style promotes deep learning by motivating students to re-examine how the key concepts they learned work in real-world examples. Furthermore, connecting key concepts that students learned from different courses provides proper context about the concepts to make the learning more meaningful and help them better retain the knowledge. Through knowledge integration, students are expected to gain a better understanding of the utility of the key concepts, and thus, facilitate students connecting the dots between topics and understand *why* they are learning the material.

The discipline of electrical and computer engineering (ECE) is a diverse and a challenging discipline for many undergraduate students majoring in this important technical field. The highly abstract nature of the materials in the key areas of the curriculum during the middle two years, namely, electronics, electromagnetics, and signals and systems, has traditionally made it difficult for undergraduate students to grasp. This has been identified as one of the main reasons for the declining retention rates for ECE undergraduate education nationally. For example, the number of American students earning bachelor's degrees increased by 16% over the past 10 years, however, the number of bachelor's degrees earned in engineering decreased by 15%. Nationally, less than 50% of the students who enrolled in engineering curriculum complete the program [1]. At Colorado State University, we typically lose 40% of our electrical and computer engineering students during the first two years of their undergraduate engineering program [2].

The causes for the declining attrition trend can be attributed to many factors from social support systems available to students, to low self-efficacy due to poor academic performance, to lack of perceived value and career opportunities relative to the amount of effort required to go through the program, to the rigid ECE curriculum structure and the lecture-style learning environment that discourage active and inquiry-based learning [1,3,4,5]

This paper describes a set of knowledge integration (KI) modules created as part of the electrical engineering curriculum for the junior year students at Colorado State University. The curriculum breaks three key junior year courses, Electronics, Signals and Systems, and Electromagnetics, into a set of learning studio modules (LSMs). Each LSM is self-contained and addresses several key concepts and a set of related concepts in a given course. Each KI module crisscrosses related key concepts from the LSMs to provide students with contextual background about the applications of the related concepts. The KI modules also provide a forum for students to discuss the relationships among the key concepts within the context of given applications.

Discussions among student groups enhance learning through self-explanation. This paper explores the motivation and process for implementing and assessing the KI modules and their associated activities. In addition, this paper also examines challenges in implementing the KI modules and potential solutions to address these challenges.

2. Knowledge Integration – A Holistic Approach to Learning a Diverse Set of Concepts in Electrical Engineering

The concept of KI is guided by well-grounded pedagogy. It has been recognized in the past as an important task in the learning process by Murray and Porter [6]. Esther Zirbel described deep learning as a process of making students question their inherent conceptual knowledge of how the world works [7]. It is well known that how students learn certain concepts and retain the knowledge is quite different from each other [8,9]. Consequently, the traditional lecture-style teaching method alone is proven to be ineffective in making sure that students learn what are taught in the classroom [10] due to its rigid content delivery mechanism and the lack of an individualized learning environment. Based on findings in cognitive sciences, it is important that key concepts are taught in an effective way that they are "absorbed" by students. However, it is more important that key concepts are connected with each other within a given context (application) [11]. Such connectedness allows effective high levels of meaningful learning and helps students retain the knowledge better. The difference between learning concepts that are connected and those that are not connected corresponds to the difference between the students either mastering the subjects with the ability to synthesize the knowledge to explain new facts, or merely remembering the concepts without the ability to apply them for new facts [7]. Also related connectedness and context, Schwab proposed that any educative event involves four elements: learner, teacher, subject matter, and context [12]. Each of these elements is important in their own right to achieve effective teaching and learning, and none can replace others in the process.

The concept of KI also aligns well with proven effective learning techniques. Donlosky et al. [13] highlighted ten effective learning techniques based on their simplicity and efficacy from the published data. Among the proven effective learning techniques, elaborative interrogation and self-explanation are ranked high. The traditional lecture-focused learning style in college-level education goes through a sequence of topics in a given area. In traditional teaching, students typically attend lectures to grasp a number of key concepts. They may interact during the lectures to get their questions answered, however, as soon as their questions are answered, further thinking typically stops. Learning through this traditional process is often superficial and students often have difficulties applying the concepts learned in the lectures to other problems not seen before. Effective teaching needs to facilitate students' ability to formulate their own answers to new problems using the key concepts they learned. Both elaborative interrogation and self-explanation emphasize continuing the critical thinking process by generating explanations through peer groups for why the key concepts are true within the context of new applications and problems. The technique of self-explanation in a group setting also promotes problem-solving skills.

2.1. Overview of Knowledge Integration Modules

KI for the junior level electrical engineering curriculum at Colorado State University starts with identifying key concepts in three important junior year courses: Electronics, Signals and

Systems, and Electromagnetics. A set of key concepts are grouped into a learning studio module (LSM). For the first semester of the junior year, there are 5 LSMs for each of the three courses. The KI modules are based on the platform of cellphone based radio system, incorporating most of the key concepts in the three electrical engineering courses during the junior year. The use of the cellphone platform allows students to apply the key concepts from the three courses to applications they are familiar with. Different KI modules focus on different parts of the cellphone-based radio system platform from power management unit, to amplifier and filter design, to electromagnetic radiation and antenna design. As students converge to KI modules over time, they will observe how the key concepts they learn are implemented and applied to a complex piece of ubiquitous technology and its system engineering.

Figure 1 shows a simplified top-level block diagram of a cellphone-based radio system. The basic functional blocks consist of the baseband subsystem for voice and signal conditioning, processing, and storage; the signal up-conversion and down-conversion at the RF level; as well as the radio transmission and receiving components, such as antennas. Some key concepts used for the baseband part of the radio system are covered by the Electronics and Signals and Systems courses; some key concepts used for the radio frequency (RF) part of the radio system are covered by the Signals and Systems course; and finally, some key concepts used for electromagnetic radiation for signal transmission and receiving are covered by the Electromagnetic course. In addition, the concepts of electrostatic field in free space and in material media taught in the Electromagnetics course are used for explaining capacitor structures; and the concepts of magnetostatic field taught in the Electromagnetics course are used for explaining speakers and microphones in the cellphone-based radio systems. It needs to be noted that RF circuit designs are not part of the KI modules. Handling of RF signals from the baseband to the carrier frequency (up-conversion) and vice versa (down-conversion) is discussed during the KI modules in terms of signal transformation only using the modulation concepts students learned from the Signals and Systems course. The need for carrier frequency in a radio system associated with antenna design (shape, size, etc.) is also discussed during the KI modules using the concepts students learned from the Electromagnetics course.

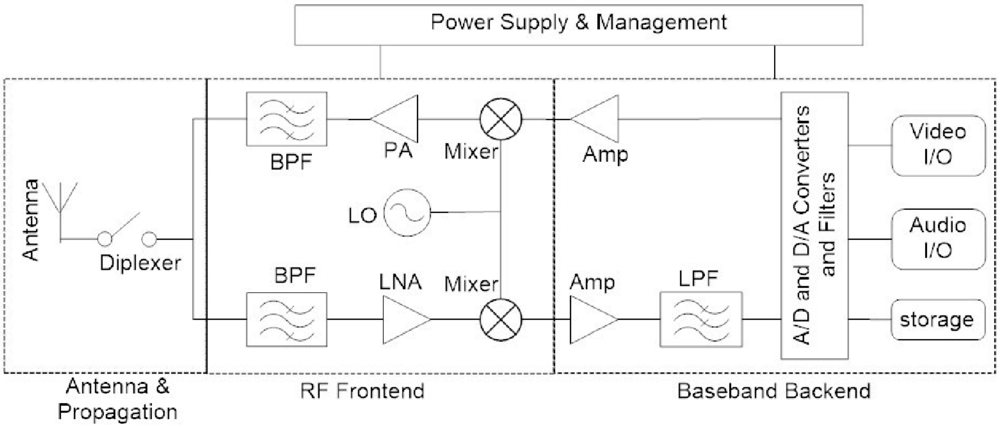

Fig. 1. The top-level block diagram of a cellphone-based radio system

Students registered in the three junior year courses are divided into groups with 3-5 students per group. Each KI has a pre-work assignment that each group must complete before the KI modules start. The pre-work consists of a list of review questions that are intended to guide students to connect a set of different concepts within the context of a given application. The interactions among students within a group promote elaborative interrogation and self-explanation. Students' understanding of the KI materials and how different key concepts are put together were tested during the in-class KI sessions where randomly selected groups were asked to present their solutions to the pre-work, and guided discussions were carried out throughout the KI sessions. The critical thinking process during the KI sessions were further aided with hands-on lab exercises before the KI sessions, or in-class live demonstrations during the KI sessions. In the following subsections, we provide two examples of the KI activities during the first semester of our junior year curriculum to illustrate the process of connecting the key concepts in the KI modules.

2.2. The First Knowledge Integration Module

Table 1 shows the key concepts in the first two LSMs for the three junior year courses during the first semester. The concepts in each LSM took 2-2.5 weeks to cover in class. The pace for each LSM for each of the three courses are synchronized that at the end of the first two LSMs, all the students from the three courses were ready to go through the first KI module. The first KI module is the DC power unit inside a radio system, specifically, the AC-to-DC power conversion unit. It integrates the concepts from the first two LSMs of the three courses

Table 1. Key Concepts in the First Two LSMs of the Three Junior Year Courses

Course	**Signals & Systems**	**Electronics**	**Electromagnetics**
LSM1	Transient and Complex Exponential Signals • Continuous & discrete-time signals • Signal energy and power • Periodic, even, and odd signals • Continuous & discrete complex exp. & sinusoidal signals • Continuous & discrete unit impulse & unit step functions and sequences	Fundamental Semiconductor Physics • Intrinsic and extrinsic semiconductors • Transport of charge carrier – drift and diffusion • PN junctions and their operations in equilibrium, forward bias and reverse bias.	Electrostatic Field in Free Space • Electric field due to charge distributions • Electric scalar potential, gradient • Gauss' Law, integral form • Gauss' Law, differential form, divergence • Conductors in the electrostatic field
LSM2	Linear Time-Invariant Systems • Linearity • Time-invariance • Impulse response • Discrete-time LTI systems: Convolution sum • Continuous-time LTI systems: Convolution integral • Properties of LTI systems: Memory, causality, invertibility, stability, and unit step response • Causal LTI systems described by differential and difference eqs.	Diodes, Diode Models and Applications • I-V characteristics of diodes – also referred to as the nonlinear diode model • Approximating the I-V characteristics using ideal diode and constant voltage models • Large & small signal diode model • Circuit application of diodes – rectifiers, voltage regulators, limiting circuits, voltage doublers	Electrostatic Field in Material Media • Polarization of dielectrics, bound volume and surface charge densities • Generalized Gauss' Law, dielectric-dielectric boundary conditions • Analysis of capacitors with homogeneous dielectrics • Analysis of capacitors with inhomogeneous dielectrics • Electric energy & energy density

Figure 2 shows a full-wave bridge rectifier circuit as a simple example of performing AC-to-DC conversion inside a power unit. Through this example, students can connect several key concepts they learned in the three junior year courses and put them together to better understand the interactions of circuits, signals, and static electrical field. For example, diodes and PN junctions were major topics in the first LSM for Electronics. At the same time, the concept of periodic signals, the impact of linearity and time invariance on circuit behavior and signal output was the focus of Signals and Systems in the first LSM. Although the full-wave bridge rectifier circuit is often used in Electronics classes as an illustration of using diodes for power conversion applications (either half-wave or full-wave), the treatment of the subject in Electronics tends to be restricted to time-domain analysis. Combining the key concepts from Signals and Systems for the rectifier application inside the AC-to-DC conversion circuit allows students to understand at a deeper level by integrating the concepts in Signals and Systems about signal periodicity, linear and non-linear transformation, and signal energy and power with diodes from Electronics. The KI also provided a practical forum for students taking Signals and Systems, which has traditionally focused on theory and analysis without a concrete circuit example.

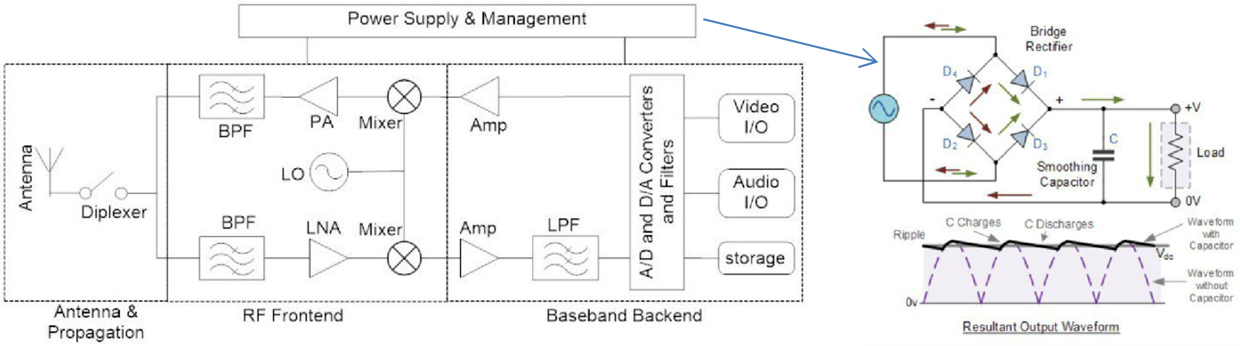

Fig. 2. The AC-to-DC conversion circuit in the power unit used for the first KI module

While focusing on electrostatic field during the first two LSMs, the Electromagnetics course also provided a fertile ground for knowledge integration with the other two courses. The concept of electrostatic field can be effectively illustrated using a capacitor, which is also a key component in the rectifier. Different configurations of capacitors using different dielectric media were explored by the students during the KI through hands-on experiments.

One of the important features of the rectifier is its low-pass filter to produce a relatively smooth DC output. In traditional electronics courses, teaching low-pass filters at this point do not typically use the concept of transfer function and convolution to derive the low-pass relationship between the input and the output of the filter. By incorporating Signals and Systems into the KI module, we were able to allow the students to systematically and rigorously derive the input-output relationship of the low-pass filter using the concepts of impulse response and convolution to gain a better understanding of its circuit behavior.

Table 2 lists a number of key concepts used in the first KI and the course(s) the key concepts are taught during the LSMs. These key concepts form the core part of the pre-work exercise the students performed before the in-class KI sessions began. Overall, the first KI module took on a simple application of full-wave rectifier incorporating a number of key concepts that were taught in the three junior year courses at the very beginning of the semester. The simplicity of the application allowed us to get students familiar with the KI format and the steps needed to complete the assignments. It also allowed us to get a better understanding of the workload required for future KI modules.

Table 2. A list of key concepts used in the first KI module

Key Concepts Used in the KI	Where the Key Concepts Are Taught
Operation of Diodes in Nonlinear Region	Electronics
Electrostatic Field in Capacitor	Electromagnetics
Capacitor for Low-Pass Filtering	Electronics, Signals and Systems
Analysis of Linear and Nonlinear Circuits	Signals and Systems
Analysis of Time Invariant Circuit	Signals and Systems
Analysis of Periodic Signals	Signals and Systems
Analysis of Signal's Energy and Power	Signals and Systems
Dielectric Breakdown in Capacitors	Electromagnetics
Impulse and Step Response of RC Circuits	Signals and Systems

2.3. The Third Knowledge Integration Module

The third KI module was scheduled towards the end of the semester when students have gone through all the key concepts for the semester. This KI utilized the key concepts taught throughout the semester to explain how a digital audio subsystem works in a cellphone-based radio system. While the second KI module (not shown in this paper due to space constraint) focused on the analog front-end of audio signal processing and amplification inside the baseband part of a radio system, it provided the necessary preparation for the third KI. Table 3 shows the key concepts in the three remaining LSMs after the first KI for the three junior year courses, where CT and DT stand for *Continuous-Time* and *Discrete-Time*, respectively.

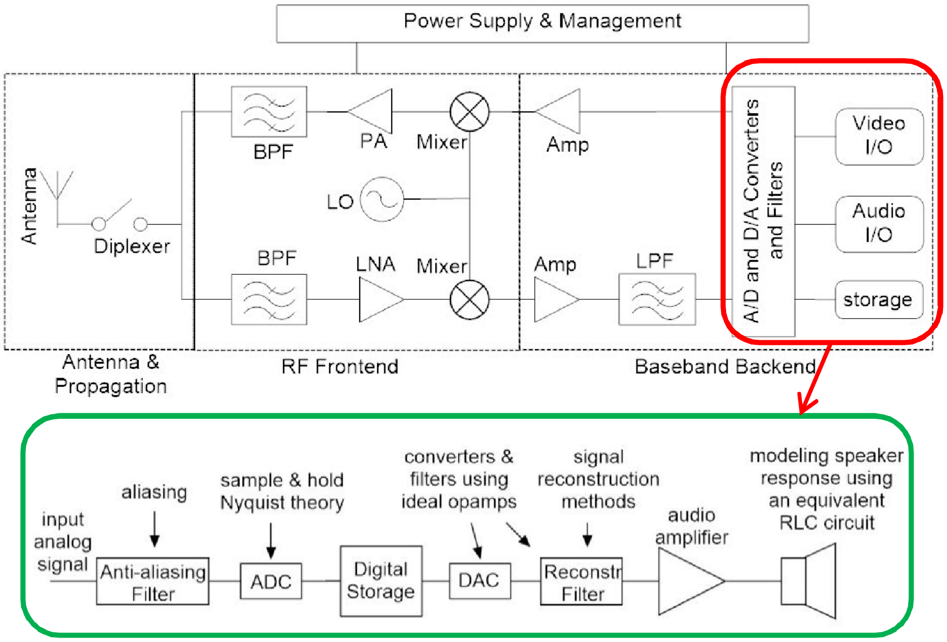

Fig. 3. The top-level block diagram of a digital audio subsystem

Through these three LSMs, spectrum analysis for both continuous-time and discrete-time are covered in Signals and Systems that led to digital sampling and the concept of aliasing. These concepts combined with the fundamental amplifier topologies and their design techniques taught in Electronics prepared students to gain appreciation of how the digital audio system works in a cellphone-based radio system. Such an appreciation was further enhanced by integrating the concepts of magnetic circuits from Electromagnetics, such as speakers, and their circuit models as RLC networks. This led to the concept of proper driver designs in amplifiers using the speaker models to provide a proper context for understanding why. Figure 3 shows the top-level block diagram of a digital audio subsystem in a basic cellphone-based radio system.

Table 3. Key Concepts in the Last Three LSMs of the Three Junior Year Courses

Course	**Signals and Systems**	**Electronics**	**Electromagnetics**
LSM3	Spectrum Analysis for CT Signals and Systems • CT complex exponentials as eigenfunctions of LTI systems • CT Fourier series and convergence • Properties of CT Fourier series • CT Fourier transform • Properties of CT Fourier transform • Magnitude and phase spectra and energy and power spectral densities • Frequency response of LTI systems: Magnitude and phase responses	Large Signal Analysis for BJTs and FETs • Operation of BJTs in active and saturation mode and their I-V characteristics • Biasing & design for BJTs for different amplifier topologies • Operation of FETs in saturation and triode mode and their I-V characteristics • Biasing & design for FETs for different amplifier topologies	Steady Electric Currents • Current Density Vector and Current Intensity • Conductivity and Ohm's and Joule's Laws in Local Form • Continuity Equation • Resistance, Ohm's Law, and Joule's Law • Analysis of Capacitors with Imperfect Inhomogeneous Dielectrics
LSM4	Spectrum Analysis for DT Signals and Systems • DT complex exponentials as eigenfunctions of LTI systems • DT Fourier series & its properties • DT Fourier transform & its properties • Duality between DT Fourier transform and CT Fourier series	Small Signal Analysis for BJTs and FETs • Bipolar amplifier topologies – common emitter, common base, common collector topologies • FET amplifier topologies – common source, common gate, source follower topologies	Magnetostatic Field • Magnetostatic Field in Free Space, Biot-Savart Law • Ampère's Law, Integral Form, Curl • Magnetostatic Field in Material Media • Generalized Ampère's Law • Magnetic Circuits
LSM5	Sampling • Shannon-Nyquist sampling theorem • Reconstruction of a signal from its samples: Sinc interpolation • Aliasing and antialiasing filters • DT processing of CT signals	Op-amp Networks • Ideal op-amp as a black box • Op-amp based networks: inverting and noninverting amplifiers, integrator, differentiator, voltage adder • Implementing nonlinear functions using op-amps: precision rectifier and square root amplifier	Low-Frequency Electromagnetic Field • Faraday's Law of Electromagnetic Induction • Computation of Transformer Induction • Electromagnetic Induction due to Motion • Self & Mutual Inductance • Magnetic Energy & Energy Density

The digital audio subsystem is shown at the top of Figure 3 with a red box. A more detailed block diagram showing the basic functional blocks inside a typical digital audio subsystem is shown at the bottom of Figure 3 with a green box. Students are generally familiar with the functionality of a digital audio subsystem as they use it on a daily basis, e.g., for playing music and using other phone audio functions. Such a familiarity provides the utility value for this KI module as students apply the key concepts to understand how the digital audio subsystem works. As shown in Table 3, aliasing caused sampling and the concepts of anti-aliasing and reconstruction were covered in Signals and Systems. The principles of constructing filters using both passive and active components (RC or Op-amps) were taught in Electronics. Students were also exposed to the basic concepts of analog-to-digital conversion and vice versa using ideal op-amp circuits in Electronics. Audio amplifiers relied on two different amplifier topologies (common-source and common-drain), that were taught in Electronics to meet the requirements for gain and driving capability for the speaker load. Finally, the principle of storing digital data on a magnetic disk using electromagnetic induction was taught in Electromagnetics. Overall, this KI pulled together many key concepts and embodied them in an application students are familiar with to allow continued critical thinking and learning in a different setting from that in the LSMs.

Similar to the first KI module, this KI module started with a set of pre-work questions to help students prepare for in-class discussions. Students worked with their group partners to come up with answers to the pre-work questions. There were three in-class discussion sessions for this KI module. The discussion sessions started with a demonstration of a custom-built digital audio subsystem with different parameter settings to illustrate the importance of the key concepts, such as sampling rate, aliasing, distortion, etc. Signal waveforms were shown at the outputs of different functional blocks to illustrate the process of signal transformation from the digital domain to the speaker output. During and after the live demonstration, a subset of groups was randomly selected to discuss their answers to the pre-work questions. Table 4 lists a number of key concepts used in the third KI and the course(s) where the key concepts were covered during the LSMs.

Table 4. A list of key concepts used in the third KI module

Key Concepts Used in the KI	Where the Key Concepts Are Taught
Sampling of Continuous Time Signals	Signals and Systems
Nyquist Sampling	Signals and Systems
Aliasing and Anti-aliasing	Signals and Systems
Two-stage Amplifier Design	Electronics
Ideal Op-amps as comparators for flash ADCs & DACs	Electronics
Signal reconstruction (op-amp and non-op-amp based approaches)	Electronics
Electromagnetic Induction Used for Digital Storage	Electromagnetics
Analysis of Magnetic Circuits (e.g. Speakers)	Electromagnetics

3. Preliminary Feedback, Challenges, and Lessons Learned

Throughout the semester, feedback from the participating students was monitored in terms learning effectiveness, work-load, contents, and balance of context with respect to three different junior year courses. Here are some preliminary findings and future corrective actions that can be taken to address these preliminary findings:

1. Students in general welcome the concept of knowledge integration and found it to be useful in helping them gain better understanding of the material at hand. However, they prefer better communication about the purposes of the curriculum change at the beginning of the semester to get them more mentally prepared for the changes that followed. A more comprehensive communication process is needed before the first KI module is acted upon to ensure student buy-in of the proposed changes in curriculum. This will significantly reduce their anxiety in the process.
2. The three KI modules took 2.5 weeks of class time out of the time originally intended for regular lecturing and other in-class content delivery activities. This caused the instructors of the three junior year courses to "squeeze" the regular planned content (listed in Tables 1 & 3) into a shorter time period in order to cover them all during the semester. This caused an increase of the overall work-load for the students. A thorough examination of the LSM contents is needed to better balance the contents taught in the LSMs and the amount of activities in the KI modules.
3. Related to work-load balance, there were many activities assigned during the week when KI modules were taught. This forced readjustment of assignments given by LSMs. Attempts were made to avoid significant overlap of assignments from LSMs and KIs during the period of KI activities.
4. The student groups formed for KI activities can be useful for learning team-work and enhance the overall learning experience, especially when partnered with someone they have not worked with before. However, the students found it difficult to start working with someone with whom they had not worked with before. A certain amount of professional training about team-work would be helpful to maximize the benefits of working within groups.

Overall, the curriculum changes of this magnitude can significantly disrupt the flow of traditional instruction. Both the faculty and the students involved need to be fully prepared for the changes. Otherwise, increased amount of anxiety, especially among students is expected. Better communication and proper balance of work-load and contents for LSMs and KIs can go a long way to help improve the effectiveness of KI and promote a better learning experience through critical thinking and problem solving.

4. Conclusions

After being awarded NSF's Revolutionizing Engineering Departments (RED) grant in 2015, the team at the Department of Electrical and Computer Engineering at Colorado State University spent many months preparing for changes of the junior year curriculum. The introduction of knowledge integration into the curriculum is intended to improve students' learning by making students to question their inherent conceptual knowledge of how the world works and by promoting their critical thinking within the context of applications. The early feedback from the students was encouraging. The early feedback also confirmed the difficulty of changing the traditional knowledge delivery and the overall resistance to change by participants (students and faculty) in general. A set of actions have been identified by the team to address the challenges in the near-term. As the department prepares for the next phase of the project, the experience we gained and the lessons we learned from implementing the KI modules will benefit the engineering education community as we seek to improve students learning experience, promote critical thinking, and ultimately improve their problem solving skills.

5. Acknowledgement

The authors acknowledge the financial support from National Science Foundation grant EEC1519438. Any opinions expressed in this paper are those of the authors and are not those of the National Science Foundation.

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