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Changes to a Circuits Lab Sequence to Encourage Reflection and Integration of Experiences Across Related Courses to Explore New Solution Spaces to an Engineering Problem

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Abstract

Engineering design requires the evaluation of trade-offs within a solution space to fit the constraints and demands of a specific application. An engineering curriculum provides its students a tailored series of courses to meet this goal. Course instructors anticipate students to regularly make connections to materials of past courses, assimilate the new information of the current course, and then explore expanded solution spaces. Disappointment arises when students fail to make these connections or often fail to recall fundamental concepts necessary to make informed decisions. In this paper we describe changes made to a junior level class to help students recall content from earlier courses on a particular topic in Electrical Engineering. This reflection better enables them to compare and contrast new material and even make connections with future course and industry solutions. Our initial survey indicates that student perception of these changes has been positive. Furthermore, a majority of the students responding to the survey suggest including similar exercises in lab modules on other topics.

1 Introduction

An important aspect of engineering education is to help students design solutions to real problems. Specifically, students need to be able to identify performance parameters, evaluate trade-offs within a solution space, and pick a non-unique solution that meets constraints and needs of the application. The available solution space is largely defined by the student's and/or team's past experiences and their ability to recognize them as relevant.

Curriculum are designed to have students progress through courses that introduce devices and gradually expand device models to provide to enrich the tool set and expand the solution space of viable designs. Lower-level courses focus largely on analytical analysis, well-defined exercises, and basic design using simple models and minimal constraints. Intermediate-level (junior-level) courses invite students to explore engineering trade-offs: pros and cons of designs that leverage on material learned in earlier classes. Courses at the senior level desire students to optimize their design for a specific application or ill-defined problems and search for better solutions when an apparent trade-off of known solutions is not satisfactory. As such, student command of engineering design trade-offs is developed over time through multiple courses.

Students are expected to make connections between courses and between theory and practice and then to expand that understanding to commercial products. The topical coverage of each course at each level and the relationship of the course sequence are obvious to the faculty but may be difficult to comprehend for a student immersed in the activities of a course and the stresses of course deadlines. Reality shows that retention of fundamental information is a challenge for most students with only a minority starting with sufficient prerequisite knowledge [1]. It might be leveraged that students benefit from reflection exercises on materials from current and prior terms [2]. The idea of an integrated approach to curriculum design with opportunities for active learning has been proposed in the past [3–11]. In [3], a mechanical engineering curriculum proposed using a desktop steam engine to help achieve the objectives of curriculum integration and providing hands-on learning opportunities for students. In this paper, we present changes introduced in an elective junior level microelectronic circuits lab course during the Fall 2022 semester to achieve certain learning objectives. The objectives are achieved through a lab exercise based on the design of Direct Current (DC)-DC converters, an object which naturally appears across many courses. Those objectives are:

1. Help students relate learning objectives in a sequence of freshman-junior lab classes in the circuits area that they have taken between their freshman and junior years.
2. Gain insight into senior-level follow-up classes.
3. Gain exposure to industry applications.
4. Explore multiple trade-offs and varied solutions to the same constrained engineering problem based on a targeted application with known constraints.
5. Use experience and knowledge to explore expanded solution spaces to a newly proposed engineering problem.

The following sections provide details on the changes that were implemented and student perception of the changes.

2 Circuits Lab Curriculum Details

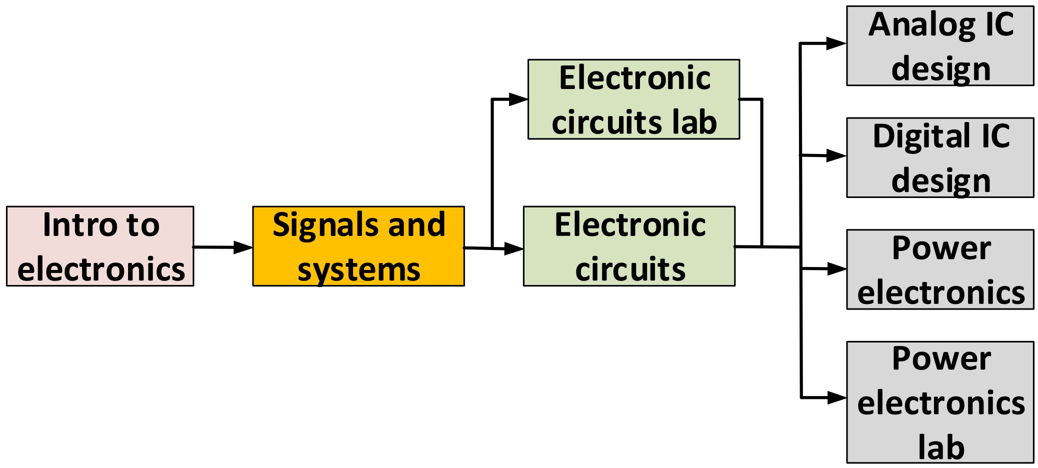


Figure 1: Circuits curriculum sequence.

The circuits coursework at University of Illinois, Urbana-Champaign is shown in Fig. 1. The curriculum begins with an "Introduction to electronics" class taken by students during their first year. The course introduces fundamental concepts and principles of electrical engineering and sub-discipline topics, including microelectronic circuits. The learning objectives focus on circuit analysis, basic electronic devices, measurement, and modelling. The course includes a lab component. Electronic circuits (ECE 342) and electronic circuits lab (ECE 343) are junior level classes that exclusively deal with diodes and transistors based circuits. Device models and types of circuits that students analyze and build are more complex than in the first year class. This class also serves as a prerequisite for follow-up elective classes in the circuits area. The elective classes include either a lab or a design project.

Students typically take electronic circuits and electronic circuits lab when they have a junior level standing in electrical engineering. By this time students have gained sufficient knowledge in different aspects of electrical engineering and have acquired the ability to understand and solve engineering problems. At this stage students are also at a point where they are ready to explore specialization areas in electrical engineering. Electronic circuits lab thus provides an opportunity to meet the objectives mentioned in section 1 and help students reflect on their learning up to this point, provide insight into follow-up classes, and gain appreciation for design challenges under different constraints.

As mentioned earlier, the new lab exercise is based on the design of DC-DC converters. DC-DC converter design appears in differing levels of complexity across the sequence of classes that students take in the circuits area curriculum shown in Fig. 1. The new lab exercise uses four DC-DC converters namely,

1. Voltage dividers
2. Zener-diode based converters

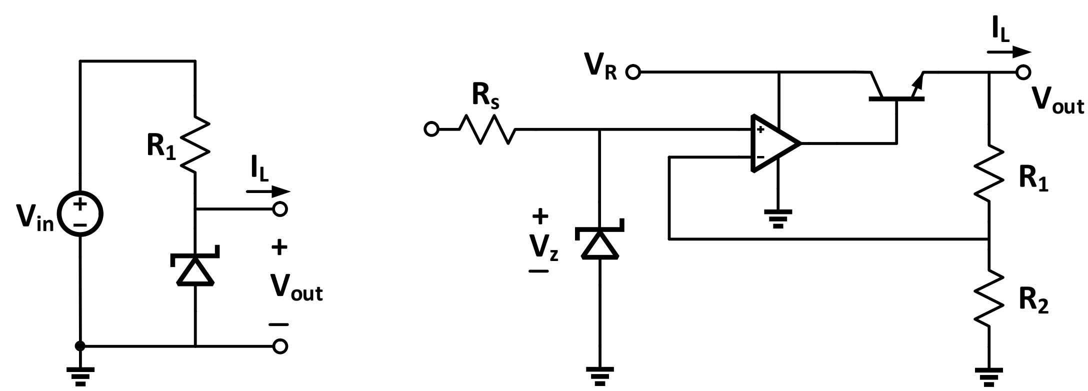
3. Low dropout regulators (LDO)
4. Switching converters

Design of a simple LDO is a part of the electronic circuits lab while students are exposed to voltage dividers and Zener-diode based converters in the first year class. Analog IC design and Power electronics lab discuss advanced LDO design and switching converters respectively.

2.1 DC-DC converter based exercises in current first year and junior level classes

In the following sections we provide a very brief overview of circuits area curriculum and the DC-DC converters based material that appears in these classes.

2.1.1 Introduction to electronic circuits



(a) DC-DC conversion in first year class.

(b) DC-DC conversion in junior level class.

Figure 2: DC-DC conversion in two courses.

The lab component in Introduction to electronics course includes the design of an autonomous moving vehicle. This design requires powering an ultrasonic sensor and a Schmitt-trigger circuit. Students have access to a $V_{in} = 9\ V$ battery while the sensor and Schmitt-trigger circuits operate at $V_{out} \approx 5\ V$. Design specification stipulate that the combined load has a current requirement of $I_L \approx 50\ mA$. Students design and implement the circuit shown in Fig. 2a. The exercise makes a mention of efficiency as a performance parameter expecting the students properly identify its role in trade-off design.

2.1.2 Electronic circuits lab

Electronic circuits lab requires students to build an AC-DC power supply that also incorporates a DC-DC converter in the form of a simple LDO shown in Fig. 2b. The converter in Fig. 2b uses a $V_z = 4.7\ V$ zener diode that is used as a voltage reference generator. The design specifications are given in terms of output voltage, ripple constraints, load current requirements. The reference generator circuit is the same to the circuit shown in Fig. 2a and also follows very similar design methodology. Since the reference generator circuit appears in a different context and student focus is on meeting design specifications, the connection to circuit shown in Fig. 2a is often missed. In addition, prior to the change described in this paper, the primary advantage (low noise) and the main disadvantage (efficiency), both being relevant in follow-up classes were not highlighted.

2.1.3 Analog IC design

The project component in the follow-up analog IC design class also requires the design of a LDO identical to Fig. 2b. The design constraints are specified in the context of analog ICs. The input-output voltage, load current, and output voltage error constrains are tighter. DC load and line regulation, noise suppression requirements, and transient response constraints are also specified. Since the design is in the context of analog IC design, size and noise requirements are important constraints.

2.1.4 Power electronics and power electronics lab

Power electronics and power electronics lab classes primarily focus on power converters (DC-DC, DC-AC, AC-DC) and controllers for the power converters. The course builds on the material discussed in electronic circuits and electronic circuits lab. Efficiency of converter circuits is an important design constraint in power electronics and the course material stresses on this aspect.

As discussed above, DC-DC converter forms a common thread across these classes. The design context, complexity, and constraints evolve over the curriculum. While design of converter is a common thread across these classes, the design constraints change and students are primarily focused on meeting requirements of the course they are in and often overlook their prior experiences.

3 Overview of course changes

In this section we provide an overview of the new lab exercises included this semester. In order to help students see engineering trade-offs, we identified efficiency, noise, and area as the three performance parameters since these parameters are important for circuits across the curriculum. The changes introduced can be classified into the following categories:

- Procedural exercises.
- Demonstration (by course staff) of a circuit designed in the follow-up class (Power electronics lab) to help students see the noise-area trade-offs.
- Reflection questions based on procedural exercise and circuit demonstration.

The exercises and reflection questions are included in sections 3.1 and 3.3 below. An illustration of circuit demonstration is shown in section 3.2. The objectives mentioned in section 1 are repeated here for easy reference:

1. Help students relate learning objectives in a sequence of freshman-junior lab classes in the circuits area that they have taken between their freshman and junior years.
2. Gain insight into senior-level follow-up classes.
3. Gain exposure to industry applications.
4. Explore multiple trade-offs and varied solutions to the same constrained engineering problem based on a targeted application with known constraints.
5. Use experience and knowledge to explore expanded solution spaces to a newly proposed engineering problem.

3.1 Procedural Exercises

The procedural exercises help students first review the different DC-DC converters they have seen up to this point and also provide insight into the types of converter circuits they will see in the follow up class. Thus these exercises help in primarily meeting learning objectives 1-2 mentioned in section 1. The main activity in this part is to compute the efficiency of each of the converters. A learning from these exercises is that the higher the conversion ratio, lower the efficiency. Students verify this on the converter circuits they have seen in lower level classes and in the converter circuit they design in the junior level electronic circuits lab class (see questions 1-3 below). Students also gain insight into converter design concepts they would see in the follow-up class (question 4).

1. Consider a common method for DC-DC conversion shown in Fig. 3. The circuit in Fig. 3 is a voltage divider. Assume $V_1 = 25\sqrt{2}\ V$. Compute the efficiency η of the voltage divider circuit for the values of V_{out} shown in table 1. You may assume $R_1 = 1\ k\Omega$. $(\eta = \dfrac{\text{output power}}{\text{input power}})$

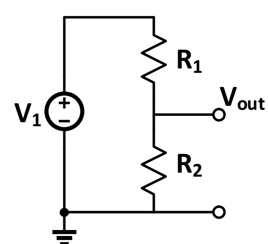


Figure 3: voltage Divider Circuit.

Table 1: DC-DC Conversion using voltage divider

V_{out} (Volts)	R_2 $(k\Omega)$	Efficiency, η
8		
4.7		
2		

2. Consider now a circuit similar to the DC-DC conversion circuit you saw in **(Introduction to Electronics)**. We designed a similar circuit in Phase 1 of this project. Compute the efficiency of the circuit shown below under full load conditions. Assume $V_{in} = 25\sqrt{2}\,V$, $R_1 = 375\,\Omega$, $I_L(max) = 20\,mA$, $V_{out} = 4.7\,V$.

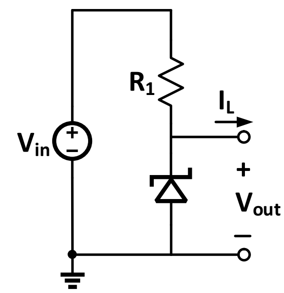


Figure 4: Zener diode based DC-DC conversion.

3. Consider the DC-DC conversion step that we implemented using the circuit shown in Fig. 5 below.

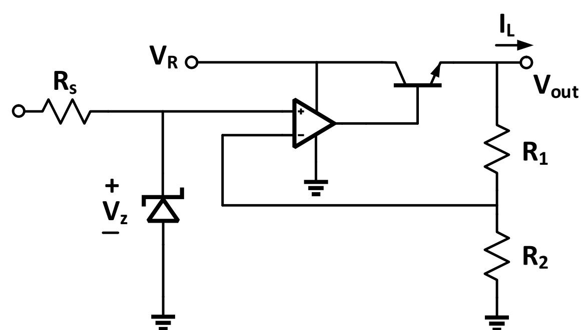


Figure 5: DC-DC conversion .

Assuming that power consumed by the transistor is the main source of power loss in the converter shown in Fig. 5, compute the efficiency of the DC regulator you designed under full load conditions ($I_L = 80\,mA$). Assume $V_z = 4.7\,V$, $R_1 = 10\,k\Omega$, $R_2 = 10\,k\Omega$, and $V_{out} = 9.54\,V$.

4. Consider the circuit shown in Fig. 6. The switches S_1 and S_2 operate in complimentary fashion. The figure also shows the switching function $\phi_1(t)$ of switch S_1. Note that $\phi_1(t)$ is periodic with period T. The switch S_1 is turned on for a duration DT during every cycle. The quantity D is called duty ratio and is given by,

$$D = \frac{\text{Time switch } S_1 \text{ is on}}{T}.$$

The circuit above represents the idea behind buck converter circuit that you will study in detail in ECE 464/469. The average value, $< V_x >$, of voltage $V_x(t)$ is given by,

$$< V_x > = \frac{1}{T}\int_0^T V_x(t)dt.$$

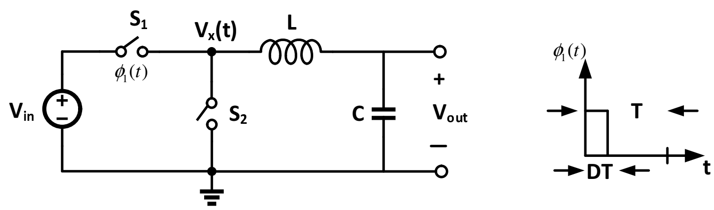


Figure 6: Switched Circuit.

Compute the value of $< V_x >$ in terms of duty ratio D.

5. The inductor and capacitor in Fig. 6, perform lowpass filtering on voltage $V_x(t)$. Assuming that all the components in Fig. 4 are ideal, what would be DC-DC conversion efficiency (in theory) of the converter in Fig. 6.

6. Observe demo of the DC-DC conversion using a boost/buck converter (based on the circuit shown in Fig. 6) used in ECE 469 class. Note down the input power and output power of the converter, and compute the efficiency of the converter.

3.2 Circuit demonstration

As part of the changes introduced, students were also shown a demonstration of the switching converter circuit they see in the follow-up class (objective 2). Figure 7 shows an illustration of observations made by students while designing the LDO based converter in electronic circuits lab and in the demonstration of the switching converter from the follow up class. Fig. 7a and 7b respectively show the components used in the two converters. The corresponding outputs obtained from the two converters are shown in Fig. 7c and 7d respectively. As can be seen from Fig. 7 the noise and size limitations (large inductor) can be observed easily by students (objective 4). Students compute the efficiency of the two circuits and observe that the circuit in Fig. 7a has an efficiency of, $\eta \approx 30\%$ and the efficiency of circuit in 7b, $\eta \approx 90\%$ (objective 4). The reflection questions in section 3.3 build on observations made by students. Through these questions students evaluate trade-offs in various situations and propose appropriate solutions (objectives 4,5).

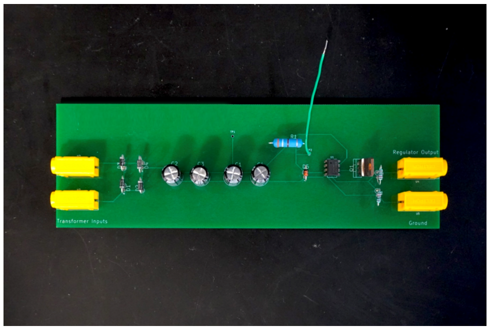
3.3 Reflection

The reflection exercises are intended to help students see the application of these circuits in real world products (objective 3), recognize that designers balance trade-offs for each application (objective 4), and explore expanded solution spaces (objective 5). The reflection questions are included below.

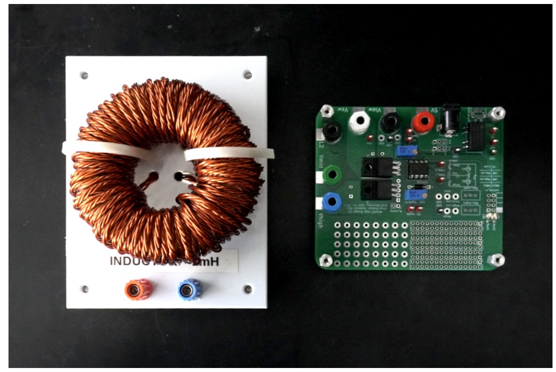
1. What are the advantages and disadvantages of each of the DC-DC converters discussed in Section 3.1.

2. Identify one application for each type circuit we discussed in section 3.1.

3. You may have noticed several solar panels on the roof of ECE building. Some of solar panels (60 in number!) are used for research purposes. One of the goals is to use these sixty panels to supply power back to the power grid. This will require converters to be designed



(a) DC-DC converter in the junior level class.



(b) DC-DC converter in follow-up class.

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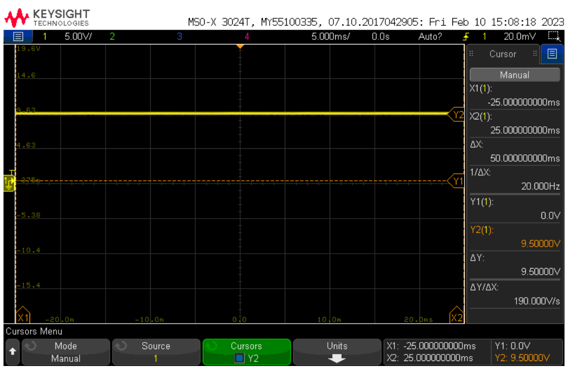
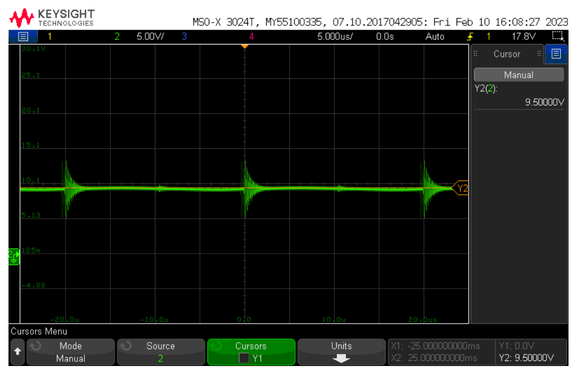


(c) Output observed by students.



(d) Output observed by students. Noise limitations can be seen.

Figure 7: An illustration of circuit demonstration.

for each solar panel. Assuming that the goal is to transfer **21kW** of power back to the power grid, which one of the converters will you pick. State your reasons.What would be the main constraint that will influence your decision? Would any additional information help you make your decision?

4. Figure below shows various components in an IPhone.Identify some analog components in the Figure.

5. Lithium-Ion batteries used in cell phones are rated at $3.7\ V$. The analog components usually operate in the range $1.2\ V - 1.8\ V$ depending on the process technology ($65nm - 180nm$). Analog components are also sensitive to noise. Would any of the methods discussed in section 3.1 work? Justify your answer. If none of the above methods work, propose a method that can be applied in this case.

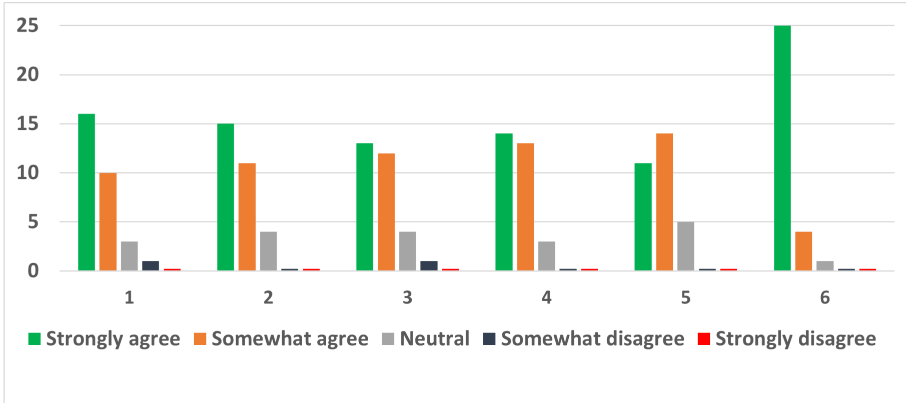


Figure 8: Student response to Lickert scale questions.

4 Student perception of changes

An anonymous survey was conducted on the completion of the exercises mentioned in sections 3.1-3.3 to collect student feedback and help the course staff gain insight on the student perception of these changes. The survey was available to all students enrolled in the class. Ninety-seven students were enrolled in the class in Fall 2022. Thirty students participated in the survey. The survey comprised of 6 Likert scale (5-point) questions, one multiple-options questions, and two open-ended questions. The six Lickert scale questions measure the effectiveness of the exercises in helping students gain an appreciation for:

1. Connections between different DC-DC conversion techniques across classes (objectives 1,2).
2. Follow-up classes in circuits (objective 2).
3. Methods and challenges in DC-DC conversion (objective 4,5).
4. Applications of electronics in commercial products (objective 3).
5. Improvements in various aspects of circuit design in the industry (objective 3).
6. Need to improve skill set.

The multiple-option question asks students to rank resources they would consider for improving their skill set in circuits and the two open-ended questions are on activities/exercises that students liked and suggestions for improvement respectively. The open ended questions can also be a measure of student interest.

Fig. 8 shows student responses to Likert scale questions where an overwhelming majority of students responded positively to these changes. The survey also shows that majority of the students (29) also believe in the need to improve their skill set. Twenty five of the twenty nine students also expressed that they would take a follow-up course to improve their skill set. This feedback reinforces the importance of helping students make connections between courses and gain insight into follow-up classes. Students responses to open ended questions indicated the usefulness of lab in helping students visualize steps from theoretical design to a complete product, opportunity to learn about different DC-DC converters, and industry applications of electronics. Student suggested improvements include having similar activities in other lab exercises and some more background material to help answer questions in procedural exercises and reflection questions. In order to gain further insight on student learning outcomes, a more detailed survey and feedback based on the work turned in by students will be done during upcoming semesters.

5 Conclusion

This paper discusses changes made to the curriculum of an elective junior level lab class. The main objectives behind these changes was to help students relate the learning objectives in a sequence of lab classes, gain insight into design trade-offs in engineering problems, see application of electronics in products, and explore new solution spaces using all of their past education on the topic. Preliminary student feedback indicates that students perception to the changes is overwhelmingly positive. Further work will involve introducing more activities that help students to relate to more areas in electrical engineering, conducting a more detailed, and measure student learning student submissions.

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