Teaching Design with a Tinkering-Driven Robot Hack

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***Abstract*—This work incorporates an open-ended design experience into an introductory circuits laboratory with the intended outcome of increasing self-efficacy for circuit prototyping and design. The authors have implemented a tinkering-based laboratory, in which students spend each lab period building a component of an inexpensive robot. The course culminates in a four week open-ended final hack that adds functionality to the finished robot. This design project prompts students to make connections across disciplines and exercise design thinking in a low-stakes environment. To determine the impact of this design experience on student learning, self-efficacy was measured through optional surveys administered both before and after the final hack. The design project resulted in a significant increase in design self-efficacy for students with some prior electronics experience, as well as an increase in prototyping self-efficacy in less experienced students, indicating that the design requirement had a positive impact on self-efficacy overall. It also showed that undergraduates in this course were ready to engage in a structured open-ended design experience even though they did not have a classical foundation in all the relevant theory, a common justification for the omission of design projects from intermediate-level engineering curricula.**

***Keywords*—Circuits education; design education; student-driven laboratory; self-efficacy.**

I. Introduction

Design is central to engineering practice, so the Accreditation Board for Engineering and Technology (ABET) recommends that undergraduate engineering programs culminate in a major capstone design experience [1]. University engineering departments have recognized the importance of exposing students to design early in their academic careers, and several have added significant design experiences through first-year cornerstone courses [2]–[4].

This paper presents a redesign of the laboratory component of a sophomore-level circuits course, *EE40: Introduction to Microelectronic Circuits*. This redesign incorporated a tinkering-based lab and open-ended design project that revolved around the construction of a simple robot. The goal of this project was to increase student self-efficacy by exposing students to hands-on circuit prototyping and design. *EE40* presents an instructional challenge because it serves all engineering and science majors, supporting nearly 400 students per semester. Therefore, the proposed design project must be broadly applicable to all disciplines and inexpensive. To enable students to propose new designs, the lab covered material more quickly than the traditional lecture sequence. Instructional video lectures were used to introduce different subsystems of the robot project. To measure the effect of the design experience on student self-efficacy, Institutional Review Board-approved surveys were administered before and after the design project to measure student attitudes towards their own abilities to prototype and design circuits for future projects.

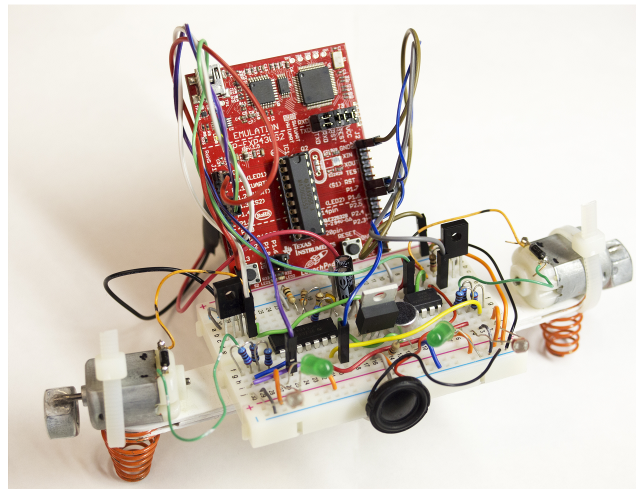

Fig. 1. The completed *EE40* robot. An MSP430G2553 LaunchPad controls the robot's behavior.

II. Lab Design

A. Motivation and Intended Outcomes

Intermediate laboratory courses often rely on simple exercises that demonstrate basic engineering science concepts rather than achieve specific learning objectives [5], [6]. These courses are missing an opportunity to engage students in a way that makes the material relevant to professional practice and that builds student self-efficacy for engineering practice [7]. Self-efficacy refers to an individual's belief in their capabilities to complete tasks and achieve a planned outcome [8]. Since engineers are expected to design complex systems upon entering the workforce, self-efficacy for engineering design is an essential outcome of undergraduate engineering education [9], and is linked to success in pursuing engineering careers

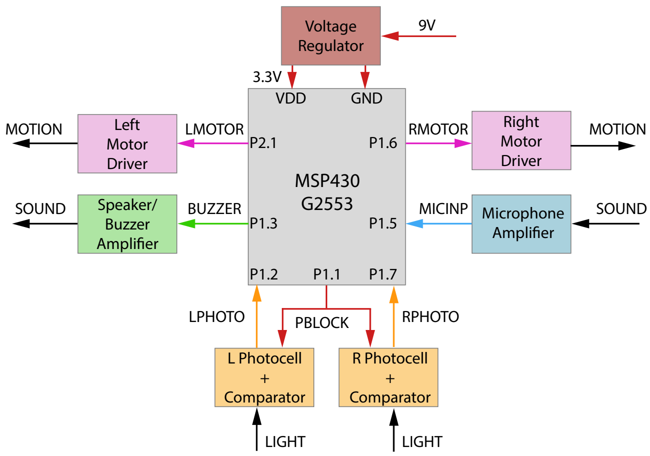

Fig. 2. Block diagram of the completed *EE40* robot project. All circuits were wired on a solderless breadboard.

[10], [11].

Project-centered learning, introduced as an instructional model over 20 years ago [12], [13], is a method to introduce more exploratory lab experiences within a well-defined problem space. Though many educators have embraced this model, incorporating project-centered learning and tinkering experiences into entry-level circuits and engineering curricula with positive results [14]–[17], these curricula often lack an open-ended design component.

Previous semesters of *EE40* employed a project-centered learning approach. Each lab section sequentially introduced a small part of an electroencephalogram (EEG) front end mixed-signal interface circuit [18]. Eventually, groups would integrate all the circuits together for their final project and record EEG or EMG (electromyogram) signals from the professor's forehead. Though the lab project successfully motivated the study of instrumentation filter design, the final project was closed-ended and left no room for students to practice design skills. To address this issue, the lab portion of *EE40* was redesigned so that each student team built a small robot that included a number of analog front end circuits interfaced with a Texas Instruments MSP430G2553 Launch Pad. Students were encouraged to tinker with the robot design throughout the semester. At the end of the semester, each team of two students was given the freedom to propose their own ideas under the guidance of their graduate student instructor.

The intended outcome of this design experience was to reinforce the theoretical material presented in the course by pushing students to carry out a design from conception to implementation. Because this experience required the students to apply circuit theory to deliver a novel, working system, it better prepared students for engineering practice than previous course revisions. As a result, we expected to see an increase in student self-efficacy for circuit prototyping (building and analyzing circuits based on their schematics) and circuit design (implementing a novel circuit).

TABLE I
LABORATORY SCHEDULE

Lab	Description
Lab 1: Soldering	Practice soldering by assembling an LED blinker circuit on a printed circuit board.
Lab 2: Lab Equipment and Programming MSP430	Learn the basics of bread-boarding and build the robots frame. Also download a program to the MSP430 microcontroller.
Lab 3: Voltage Regulator	Learn why voltage regulators are used and build the voltage regulator circuit.
Lab 4: Resistors	Learn about interfaces with resistive sensors. Build resistive front ends to add light sensors to the robot.
Lab 5: Amplifier Circuits	Build a speaker driver and an electret microphone amplifier.
Lab 6: Capacitors and Filters	Explore the frequency response of RC filters to understand why they are used in other circuits on the robot.
Lab 7: DC Motors and Transistors	Build BJT-based DC motor driver. Describe FET amplifier in electret microphone.
Lab 8: More Filters	Build more filters and learn about their applications.
Labs 9, 10, & 11: Final Hack	Three weeks to prototype and debug the final design project.

B. Robot Platform

Each student team was required to build a robot based on the one shown in Figure 1 that included a number of analog circuits interfaced with a Texas Instruments MSP430G2553 microcontroller. A block diagram of the completed robot system is shown in Figure 2. The robot components consisted of inexpensive household supplies and common electronics; wooden craft sticks comprised the frame while springs and eccentric weight motors comprised the drive train. During each lab section, students built a few circuits that enhanced the sensing or actuation capabilities of the robot while expanding upon core concepts in circuit theory.

The robot subsystem schematics are shown in Figure 3 and the lab schedule is shown in Table I. By the end of the lab, students had built and integrated a number of circuits and had a starting platform for their final hack. Each circuit was simple, suggesting potential areas for improvement to interested students. The physical lab space was stocked with excess resistors and capacitors to facilitate tinkering and engagement with the robot circuits.

The simple robot design invited the addition of new circuits that were not explicitly discussed in class, a critical step because it required students to actively synthesize new knowledge rather than passively consume it. By demonstrating that a simple robot could be built from household parts, students would feel motivated to implement their own ideas and be less intimidated by the design project.

C. Online Video Modules

In order to enable students to propose new designs, the lab covered supplemental material more quickly than the traditional lecture sequence. To cover this material, instructional

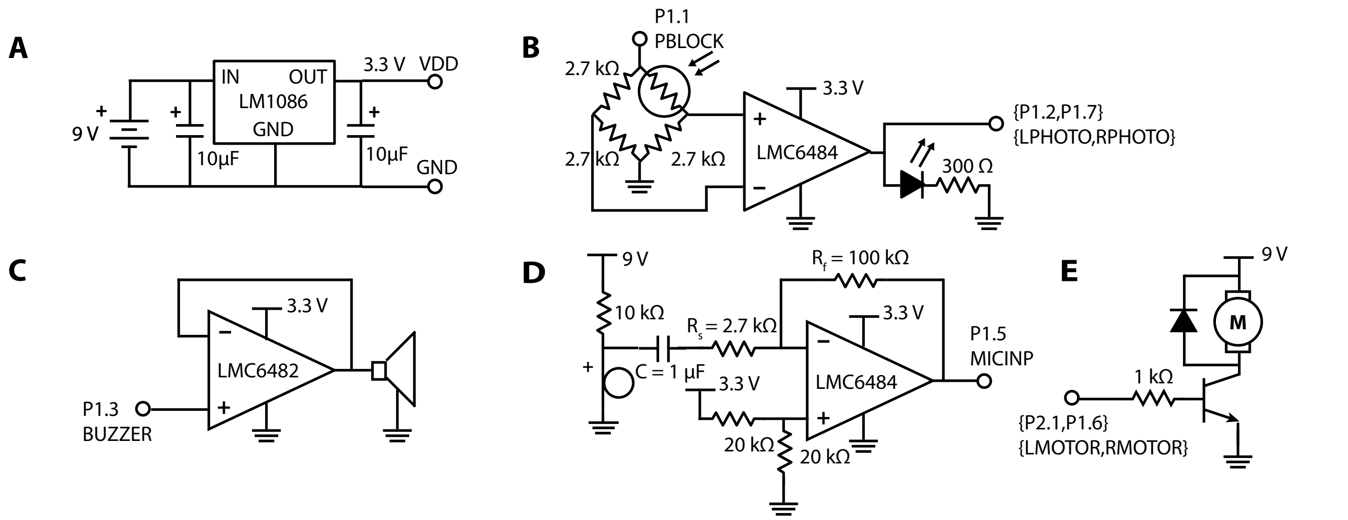

Fig. 3. Robot platform schematics include A) a voltage regulator, B) two photocell-comparator front ends, C) a speaker driver, D) an electret microphone front end, and E) two motor drivers.

video lectures that introduced different aspects of the robot project were recorded. These short (6-10 minute) lectures were delivered online through the edX Edge platform. This instructional model is known as a small private online course, or SPOC [19]. Because these robot videos were a self-contained series, they were later made available to the public as part of a massive open online course [20].

D. Final Hack

Once each group of students completed their robot base, they proposed a "final hack," a new circuit that would add functionality to the robot, with guidance from a graduate student instructor. Since design projects typically come later in the curriculum, there was a concern that students would not have enough background to propose their own circuits. Therefore, several sample hacks were specified as options for less proficient groups.

Each student group submitted a proposal to get feedback on their ideas. After the initial feedback, the groups had a four-week period to work on their final hacks with three lab sessions and one break week for a midterm. A quick sampling of the diverse projects demonstrates the class' enthusiasm:

- Infra-red beacon detection
- Radio controller
- Analog line follower
- Firefighting robot with infrared flame detector and motorized fan
- Electromagnetic metal scavenger

III. Methods

A. Survey Design

This laboratory was administered during the Fall 2014, Spring 2015, and Summer 2015 sessions. During the latter two sessions, an Institutional Review Board-approved mid-course survey and an exit survey were administered to determine the effects of the design experience on student self-efficacy.

TABLE II
Survey Questions

Background
What is your major?
Do you consider yourself a "maker" or work on hardware projects as a hobby?
Section 1: Prototyping self-efficacy scale
I can explain how circuits operate in real-world applications.
I am confident that I can debug and fix circuit issues when they arise.
If I come across a new circuit, I can figure out how it works with some effort.
Section 2: Design self-efficacy scale
I believe I can design an interesting application for the final hack.
My group's final hack will be a success.
I can improve on the design of some of the circuits on the robot.
I will be able to appropriately allocate my time to complete my group's final hack.
I am nervous about the final hack.
Section 3: Laboratory evaluation
I have learned a lot from my experience in this lab.
The lab exercises have been interesting and engaging to me.
The lab significantly extends my understanding of the course material.
I have enjoyed the time I have spent in lab.
I found that the lab was frustrating most of the time.
The lab exercises were often confusing and/or unclear to me.

The entire survey is presented in Table II. In the first section, each survey participant was asked to identify his/her major and whether or not he/she self-identified as a "maker" or electronics hobbyist. The next two sections measured circuit prototyping self-efficacy and design self-efficacy attitudes on scales that consisted of several statements about circuit proto-

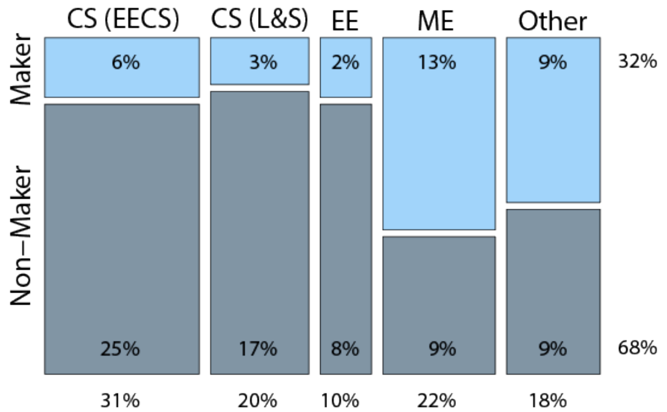

Fig. 4. Student backgrounds in Spring 2015 (N=109). These results are representative of all sessions. The student majors are represented on the horizontal axis and identification as a maker or non-maker is represented on the vertical axis. Some percentages do not add to 100 due to rounding.

typing and design. The respondents were asked to judge how they agreed, using 5-point Likert-style response items (+2: "strongly agree," +1:"agree," 0:"neither agree nor disagree," -1:"disagree," and -2:"strongly disagree"). Numeric values were averaged to obtain a point value for each scale. The final survey section asked students to evaluate the lab course and design project and consisted of six questions. Respondents were also asked to provide written feedback.

B. Course Evaluations

Every semester, the student chapter of Eta Kappa Nu has independently collected course and instructor evaluation surveys for all electrical engineering course offerings. These survey results are publicly available online and *EE40* ratings are accessible for every semester from 1988 [21]. Because *EE40* has been taught by the same instructor every Fall and Spring semester since Fall 2011, these evaluations provide a useful baseline for comparison of this redesign to previous semesters.

IV. Results and Discussion

A. Student Demographics are Varied

The breakdown of the survey respondents by major for the Spring 2015 session, which is representative of all sessions is shown in Figure 4 (N=109). The abbreviation EECS stands for Electrical Engineering and Computer Science and allows students to choose either a computer science (CS) or electrical engineering (EE) focus. This university also offers a degree in computer science from the College of Letters and Sciences (denoted here as CS L&S). This course primarily serves EECS, CS, and mechanical engineering majors. The Other category was diverse, including non-engineering majors, and Bio, Chemical, Materials Science, and Physics Engineering majors.

From the results, it is apparent that *EE40* primarily serves computer science majors, who made up 51% of all survey respondents. Of the survey respondents, 32% self-identified as "makers" and have tinkered with electronics before out of personal interest. Makers tended to be outside of this course's core discipline of EECS, with the majority being Other (28% of makers) or ME majors (31% of makers).

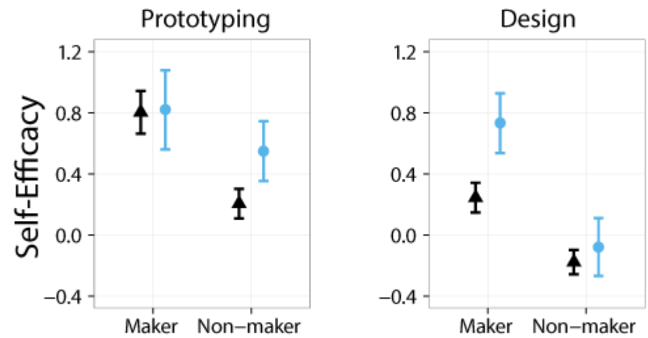

Fig. 5. Mean prototyping and design self-efficacy survey results for makers and non-makers. The triangles are the results before the final hack (N=127) and the circles are the results after the final hack (N = 56). The bars mark the standard error.

B. Design experience increased design self-efficacy in makers and prototyping self-efficacy in non-makers

The results of the combined course surveys are shown in Figure 5. Makers, who came to the course with some electronics experience, did not experience a significant increase in their prototyping self-efficacy after the design project. However, non-makers did demonstrate a significant increase in their prototyping self-efficacy. The self-directed tinkering that occurred during the final hack may have improved confidence for these relatively less experienced students, to the point where the measured difference between maker and non-maker self-efficacy was within the standard error.

Students approached the design project with some caution, as evidenced by lower pre-hack self-efficacy scores (+0.20 for makers versus -0.18 for non-makers). The design experience did little to change design self-efficacy in non-makers (-0.08 post-hack), but makers experienced a significant increase as a result of their experience (+0.55 post-hack). These results suggest that students with some prior circuit building experience benefited the most from the final hack, likely because the project allowed them to apply their prior practical electronics knowledge in a formal laboratory setting.

C. Course evaluations improved due to the design project

The results of the class evaluation surveys were combined between the Spring 2015 and Summer 2015 sessions and are presented in Figure 6. The same questions were asked both before (N=127) and after (N=56) the final hack. The overall class evaluation is more positive after the final hack. Before the design experience, the lab had a traditional format where students followed a lab script to build and measure a few standard circuits. The evaluation of the lab though already positive, improved after the open-ended design experience.

Standard course evaluations of *EE40* were used to compare this session to previous years. Course evaluations from Fall

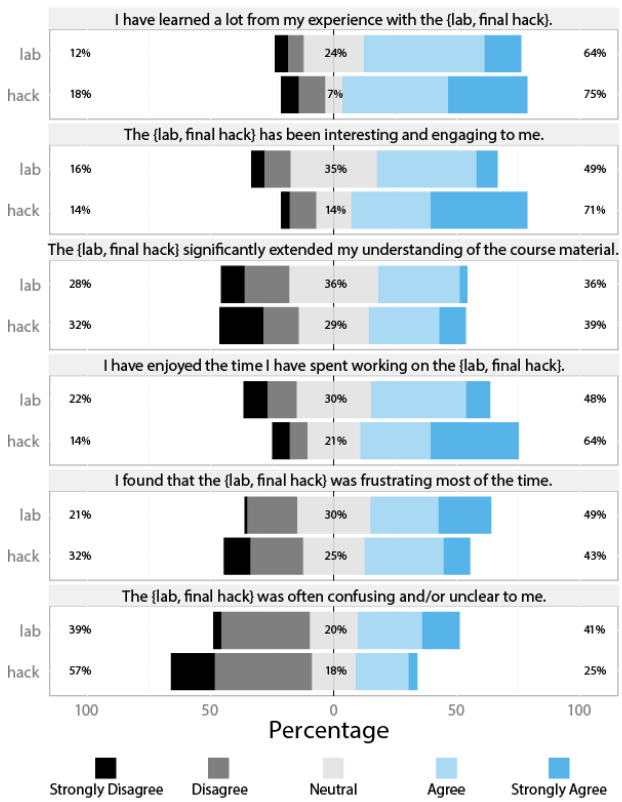

Fig. 6. Course evaluation ratings measured before and after the final hack.

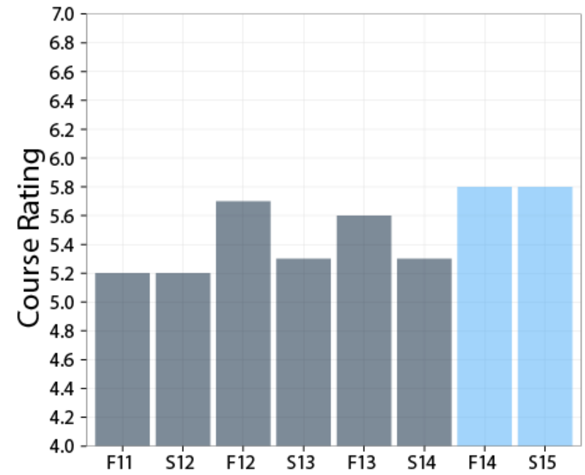

Fig. 7. *EE40* course evaluation ratings from Fall 2011 to Spring 2015. The laboratory redesign described in this work was used during Fall 2014 (F14) and Spring 2015 (S15). Summer sessions are omitted because these courses were taught by different instructors.

2011 to Spring 2015, independently collected by the student-led Eta Kappa Nu chapter, are plotted in Figure 7. The Fall 2014 session was the highest rated semester of *EE40* that was ever taught by this professor (5.8/7.0). The Spring session, which has historically lower ratings, was also the most highly rated Spring session taught by this professor (5.8/7.0). The mean course effectiveness of *EE40* from 1988 to the present day is 5.2 with a standard deviation of 0.57. Even though significant effort had already been spent into improving *EE40* with a project-based curriculum [18], this redesign effort resulted in further improvement of its effectiveness ratings.

V. Conclusion

The authors have integrated a novel tinkering-driven laboratory and design project into a sophomore-level circuit analysis course with the intended outcome of increasing student self-efficacy in circuit prototyping and circuit design. This was an instructional challenge due to the large class size and variety of student backgrounds. In response to these constraints, the robot materials were kept inexpensive and lab videos were developed to provide supplemental practical instruction. The design experience had a positive effect on most students, who rated the course more highly after they completed the design experience. Those students who had prior experience with electronics or robotics, self-described makers, saw a significant increase in their design self-efficacy as a result of the design project, while non-makers saw an increase in their circuit prototyping self-efficacy. Further work could be done to better prepare non-maker students to successfully complete a design, particularly with targeted instruction for simple microcontroller programming and time management.

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