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Design of a Curriculum-Spanning Mechanical Engineering Laboratory Experiment

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Abstract

This paper describes a laboratory experiment that was designed to facilitate education in material science, instrumentation and controls, and thermal sciences. The laboratory module is part of a broader effort to enhance mechanical engineering laboratory curriculum to incorporate modern pedagogical methods and to improve a defined set of student outcomes.

The laboratory experiment focuses on a low-cost toaster oven that has been modified to allow students to control temperature and fan operation through either LabVIEW or Arduino systems. The oven experiment has been designed to facilitate long-term testing in the material science laboratory, sensing and control of the temperature in the oven during the mechanical systems laboratory, and precise heating of specimens during the senior level thermal systems laboratory.

To assess the effectiveness of the laboratory experiment a student survey was administered and results indicate the new laboratory experiment has been successful in improving student engagement.

Introduction

This paper describes a set of laboratory modules based on a low-cost toaster oven that students encounter throughout the mechanical engineering curriculum. The toaster oven project is part of a larger effort by several mechanical engineering faculty to enhance the entire laboratory curriculum. The laboratory curriculum enhancement includes two facets:

1. Modernize and improve the technical skills acquired by students in the laboratory courses.
2. Thoughtfully incorporate developmental skills (soft skills like teamwork, communication, etc) that are important for engineers.

The goal of the overall project is to improve how students learn particular aspects of mechanical engineering laboratory courses across the full four-year curriculum, using evidence-based instruction methods and assessment. The methodology included inquiry-based learning (IBL) and backward design to create laboratory modules in the curriculum to meet learning objectives, rather than teaching lab courses where students “cook” with a recipe.

The original mechanical engineering laboratory curriculum includes 1-2 credit courses that occur after students complete relevant lecture courses. For example, students would complete thermodynamics and heat transfer before enrolling in a 1-credit thermal systems laboratory. Because the laboratory courses are separate from the lecture materials, they offered an opportunity to improve developmental skills and flexibility. A backward design pedagogical method was adopted to build the new laboratory curriculum following the model of a successful implementation of a design elements through the curriculum [1].

The larger effort for the laboratory curriculum design led to a thoughtful conversation about the best ways to incorporate developmental skills and new technical skills. One mechanism became scaffolding of simple laboratory equipment through the multi-year laboratory courses. Past research in education has found that scaffolding knowledge improves student educational outcomes [2]–[4]. The goal of this project was to develop a laboratory module that allowed students to build on prior knowledge of specific experimental equipment.

An important feature of all the new laboratory modules became open-ended laboratory outcomes for students. Many of the older laboratory experiments include some equipment that has been in service for more than 20 years. Many students entered the lab and listened to a short lecture or introduction on the equipment by the faculty. They then performed an experiment using one large piece of equipment that offered little or no interaction for most of the students.

For example, in the undergraduate thermal science laboratory the students traditionally performed an experiment using an evaporative cooling tower. An overview of the equipment was provided by the instructor along with a handout of the laboratory procedure. The students take a few minutes to ask questions about the equipment and speculate about how analog instruments might work. Then a few students participate in turning valves or pressing buttons to initiate the experiment. The remaining 16-18 students write down numbers and read the lab handout (or quietly begin catching up on text messages). After the lab is complete the students leave quickly and write a lab report that will mirror closely the lab reports of all other students in the course. The goal of this lab activity in the older system appears to be “learn how an evaporative cooling tower works”.

The issue with this type of laboratory experiment is that it does not do much to develop the student for a career in modern engineering. While understanding how an evaporative cooling tower works may provide value to a few of the students, it is impossible for the faculty to expose students to every type of system, in only one semester. What will provide more value to the undergraduate student is a focus on open-ended problem solving, teamwork, and experimental design.

Background

The science of engineering education has advanced significantly in the last few decades. Several methods emerged that may provide measureable improvement in traditional laboratory courses including deep learning approaches, backward design, and concept inventories. Nelson, and other education pedagogy experts, provide a succinct summary of deep learning approaches that may be adapted for engineering education [5]. Deslauriers has validated many of these approaches in the context of STEM courses [6] and they may be incorporated in laboratory courses to maximize student achievement on technical concepts.

Concurrently, backward design and deep learning approaches may improve the professional development of students through developmental learning objectives. Kuh [7] has identified a list of learning outcomes that employers consider essential that may be tied to mechanical engineering laboratory courses using backward design, specifically: Self-direction, timeliness, cogent writing, critical thinking, adaptability, quantitative reasoning, social responsibility, teamwork and collaboration.

Efforts have been made by prior researchers to utilize evidence-based instruction in engineering laboratories. Kanter et al. introduced inquiry based learning in one biomedical engineering laboratory course and reported very positive results [8]. Flora et al. enhanced one introductory environmental engineering course [9]. They found that the open-ended approach was appreciated by the students, particularly female students. None of the prior investigations attempted to integrate the enhanced laboratory design across a four-year engineering curriculum or to explicitly include developmental learning objectives.

The goal of the research team was to develop a comprehensive, sustainable and replicable laboratory curriculum that used each laboratory module to facilitate technical and developmental learning objectives. The laboratory curriculum will eventually span the four years of an undergraduate engineering education. Each module will include the following features:

- Specific student learning objectives (technical and developmental)
- Structure that encourages self-direction and critical reasoning rather than recipe reading
- Interaction with modern equipment and tools that students are more likely to encounter in industry (programming, modern instruments, data acquisition, etc.)
- Designed to be inexpensive and easy to implement by other universities

The use of student learning objectives is an established effective teaching method from the education experts, sometimes referred to by other names including constructive alignment [6], [10], [11]. Course design that utilizes learning objectives has been tested by many researchers in the last 15 years. Among engineering educators the leaders in backward design include Felder and Prince, who document the idea in engineering education literature, but also at annual training workshops for engineering faculty [10], [11].

Equipment Design

The toaster oven module is a new multi-lab module to be used in the materials lab by second year students, mechanical systems lab by third year students, and the thermodynamics lab by seniors. The new toaster ovens were designed to be encountered by students sequentially in each laboratory class as they progress through the curriculum. The main purpose of the module was to create a system where a low-cost oven can be completely controlled via a computer. This allows for temperature profile and exact temperatures to be maintained for a variety of applications.

Since the faculty group was working as a team, we were able to design a laboratory module that could be used through the entire curriculum. The sophomores see the oven in a second year material science lab as it is used to heat specimens, and for them it is a sophisticated oven that records temperature. However, the next year in a systems and measurement laboratory the same students program the oven to create very specific temperature/time histories. Then, as seniors, students use the same oven in thermal systems laboratory for heating items and analysis of temperature change over time. This type of continuity between the labs will help the students' focus on learning new skills rather than new equipment.

The oven module was constructed by modifying an inexpensive toaster oven as shown in Figure 1. After the oven was disassembled, the timer and function dials were removed, as well as the rotisserie motor. The temperature selection dial was left on, since it works based on a mechanical thermostat. This mechanical thermostat provides over-temperature protection if the student's program controlling the temperature fails. Inside the toaster oven, a thermocouple probe was added to allow temperatures to be monitored and to be used as the input for the program students write. The top and bottom heat elements, and the convection fan, are all separately controllable by the use of relays on the added circuit board. The circuit board uses a 5V control voltage, supplied by a power converter. The controls to the circuit board can run on 5V to 24V added voltages. This allows for control via Arduinos, NI-DAQs and LabVIEW, or PLCs, all different types of equipment covered in the laboratory curriculum. The completed toaster oven was enclosed as it was before the modifications, with the only external change the three female banana plugs and a thermocouple plug protruding from the side, allowing for the sensing and control.

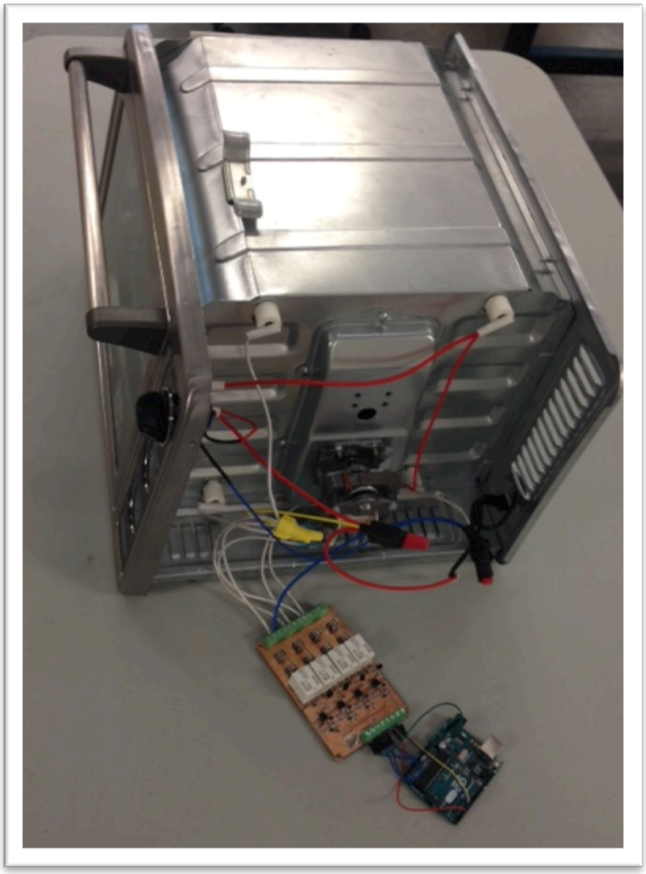


Figure 1. **Modified** oven shown with added components exposed.

The toaster ovens were designed to allow teams of students to control many aspects of the heating process. In materials lab, the ovens will be left on for long periods of time at low temperatures and varying profiles to demonstrate the phenomena of creep. They may also be used to study other material properties and how they change with different temperatures; however, the maximum allowable temperature for the ovens is 450˚F. In the mechanical systems lab, the actual programming of the toaster ovens is investigated and students learn to control them using Arduinos and LabVIEW. In the thermodynamics lab, materials are heated at different rates to differing temperatures, and removed to test the heat transfer. Finally, the toaster ovens can be used as surface mount reflow soldering ovens for the electrical engineering students, aiding in the ease of production of circuit boards.

The toaster oven module was designed to be low-cost oven as shown by the component list in Table 1.

Table 1. Summary of components and costs associated with the toaster oven module.

Component	Part Number/Serial Number	Cost per Oven
Toaster Oven	Farberware Model# 103738	$40.00
Arduino	Uno v3	$20.00
PCB	N/A (see PCB documentation)	$16.60
Fuse (x3)	Bel Fuse 5ST 10-R	$0.55
Capacitor (x3)	10 nF	$2.60
Pin Connector (x5)	Phoenix Contact 1729144	$9.15
Diode (x6)	Vishay 1N4148W-E3-08	$0.35
Fuse Clip (x3)	Littelfuse 01000020Z	$1.40
Surface Mount LED (x3)	Lumex SML-LX1206GC-TR1	$0.30
MOSFET (x3)	NXP 2N7002P,215	$0.35
Opto Coupler (x3)	Lite-On LTV-816S	$0.50
Bipolar Transistor(x3)	NXP MMBT3904,215	$0.25
Relay(x3)	Omron G5LE-1-E-DC5	$6.15
Resistor(x3)	200 Ohm	$0.25
Resistor(x3)	750 Ohm	$0.30
Resistor(x3)	10K Ohm	$0.75
Resistor(x3)	1K Ohm	$0.55
Resistor(x3)	470K Ohm	$0.25
110VAC to 5VDC Converter (x2)		$10.00
Thermocouple	Omega KMQSS-125G-6	$27.00
Thermocouple Amplifier	MAX31855	$14.95
Total		$152.25

Laboratory Module Design

This project used backward design for the curriculum development, based on several outcomes planned for the different laboratory courses. The oven facilitated both technical and development outcomes for students. The research team developed the following objectives as key elements of the senior level thermal systems laboratory that the oven modules might facilitate. Other laboratory classes at the sophomore and junior level have separate objectives for the ovens appropriate for each class.

Technical objectives:

- Develop a simple code to record data (typically thermocouples) at a specified time interval and save the data to a file.

- Estimate the convection coefficient for a real system using experimental values like temperature, material, and geometry.
- Determine thermodynamic properties using measured experimental data (pressure, temperature, relative humidity, etc).

Development objectives:

- Employ proper citations and references in all formal written work.
- Negotiate and resolve conflict independently within the group.
- Discuss independent experimental plan and ideas with classmates and instructor.

The thermodynamics laboratory oven modules were the first to be implemented and the experiment designed was the focus of the existing assessment for the ovens. The laboratory handout was designed to facilitate the objectives in different ways. The students were assigned to small groups of three, and each team was provided a modified oven. For the first laboratory module, the students developed a simple control method to hold the oven temperature at a specific set point and record temperature and time. This allowed them to practice "*Develop a simple code to record data (typically thermocouples) at a specified time interval and save the data to a file.*" The student teams were allowed to choose either Arduino or LabVIEW for the control and data acquisition system based on prior knowledge. While none of the student teams had used Arduino before, all groups except one decided to use a new tool so they could gain a new skill.

The students were not provided a specific laboratory outcome to measure, rather each group was tasked with baking the "perfect" cookie. Since "perfect" is a subjective measure for cookies, each team was then forced to define what the best way to measure a perfect cookie might be. This allowed the students to "*Negotiate and resolve conflict independently within the group*" in a safe environment where nearly every student was a confident subject expert.

The only constraint was that the center of each cookie must reach a safe temperature to kill salmonella at approximately 160^{o}F [12]. The students were asked to make a plan to ensure that the experimental cookie would be safe to eat. This allowed students to "*Discuss independent experimental plan and ideas with classmates and instructor."* All the students quickly discovered that in order to calculate the cookie temperature in the oven they would need to estimate the convection coefficient and look up thermodynamic properties using measured experimental data (*Estimate the convection coefficient for a real system using experimental values like temperature, material, and geometry; Determine thermodynamic properties using measured experimental data*). At the conclusion of the laboratory experiment the students wrote a laboratory report documenting the data acquisition and practicing citation and references. Each laboratory report was unique, and varied based on how teams controlled the ovens and measured cookie perfection.

Student Observation Assessment

As the first oven module implemented, the cookie experiment was assessed in several ways. A faculty member trained in educational assessment attended the laboratory and posed several questions to the students during the experiment, including asking about the level of control they might notice over the experimental outcomes. Photos illustrating the engagement are shown in Figure 2.

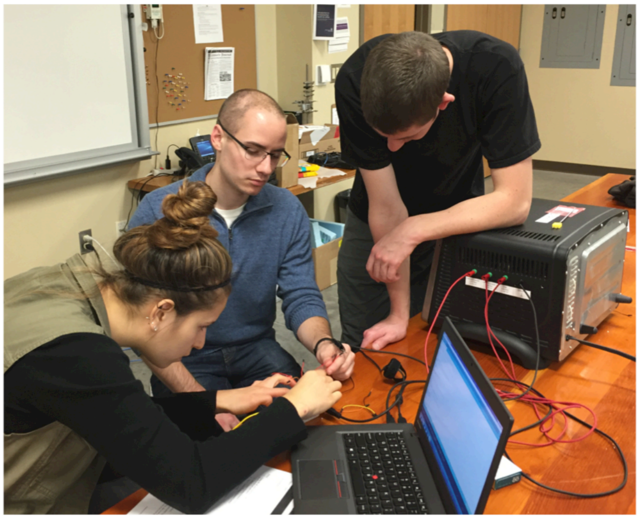


Figure 2. Students gathered around the ovens during a laboratory class.

- Group 1: Students compared Arduino to LabVIEW to pick the best control system and picked LabVIEW based on prior knowledge. Students also expressed that each student had a job to do, but they would communicate frequently to accomplish the experiment.
- Group 2: Students discussed convection, conduction and radiation heat transfer modes prior to deciding what the best control method might be.
- Group 3: Observed that they needed to work together since the laboratory required knowledge from several prior courses. They also commented that they had significantly more control than the prior cooling tower laboratory, that experiment had only one outcome.
- Group 4: Noted that they were designing the experiment rather than following a script like they did on the cooling tower last week.
- Group 5: Observed that they had more control and they appreciated that they were already familiar with ovens even though this one had been modified. They noted that what we’ve always taken for granted that has been separated out on these ovens.

The educational observer also made a few global comments about the laboratory class.

- Each member of the student teams are fully engaged, although it looks different in several of the groups. Several of the groups separated the wiring activities from the code writing.
- One student team sent an ambassador to another group to get advice on a wiring issue they encountered.
- None of the students appear to have disengaged in the laboratory. Technology was used only in support of the experiment and data gathering.

A few student comments during the observation were also interesting and hint at the elegance of using simple equipment in laboratory courses, “My prior knowledge of cookies and ovens meant I was able to concentrate on new stuff: Arduinos, the language of the experiment—unlike the evaporative cooling towers lab last week, which was all new." Another student offered a pragmatic view while examining a burned cookie, "At least we learned how to use Arduinos."

Survey Assessment

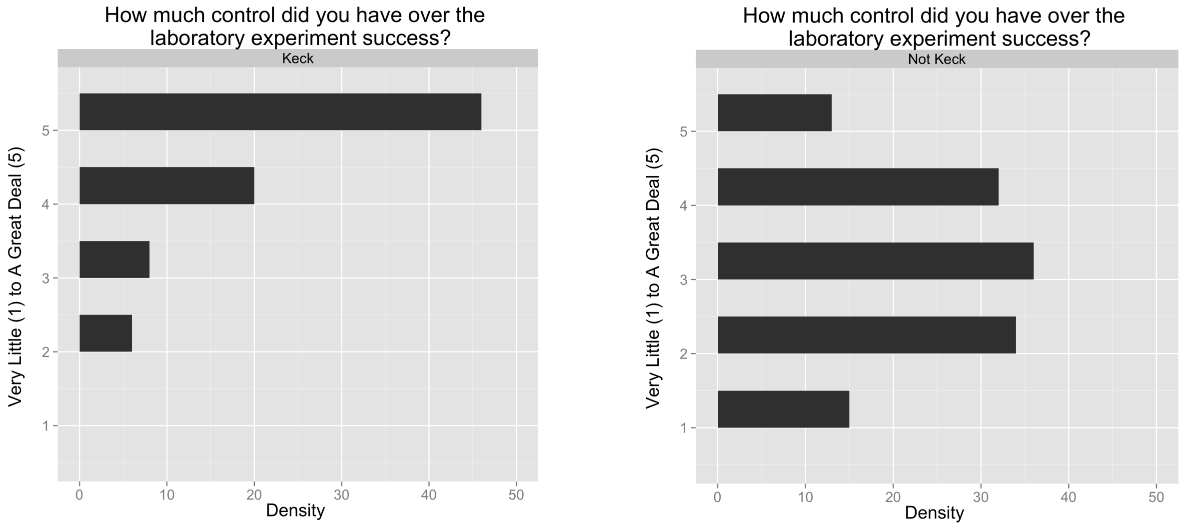
To assess how student's perceived the experimental module outcomes a survey was administered to senior level students in the Fall of 2015 at the end of the semester. 27 students completed the survey in a class of 29, representing a 93% response rate. The survey asked the students to rank how they perceived each laboratory module in the course. To allow comparison, students were asked to evaluate all the laboratory modules in the course, although only three of the modules were open-ended, and only one of the modules focused on the oven.

An example question from the survey is shown below. An asterisk has been added to experiments that were designed to be open ended.

1. Rank the following laboratory experiments based on how much control you had over the laboratory experiment success (how open-ended was the lab)?

Laboratory Module	How much control did you have over the laboratory experiment success? Circle one.				
	Very little control				A great deal of control
Solar Water Heater	1	2	3	4	5
Specific Heat	1	2	3	4	5
Engine Dyno	1	2	3	4	5
Evaporative Cooling Tower	1	2	3	4	5
Toaster Oven*	1	2	3	4	5
Wind tunnel cooling*	1	2	3	4	5
Schlieren cooling	1	2	3	4	5
Boiler project*	1	2	3	4	5

The results from this question are shown in Figure 3. The average response for all the laboratory modules was 3.48 with a standard deviation of 1.28. The three open-ended laboratory modules included the toaster oven, the wind tunnel, and the boiler project. For these laboratory modules the average response was 4.33 with a standard deviation of 0.94 indicating the students clearly perceived the experiment as primarily in their hands without a predefined outcome. For the oven module the average was also 4.33 with a standard deviation of 1.04, confirming that the oven module as perceived by the students to give them a great deal of control over the experiment outcomes.



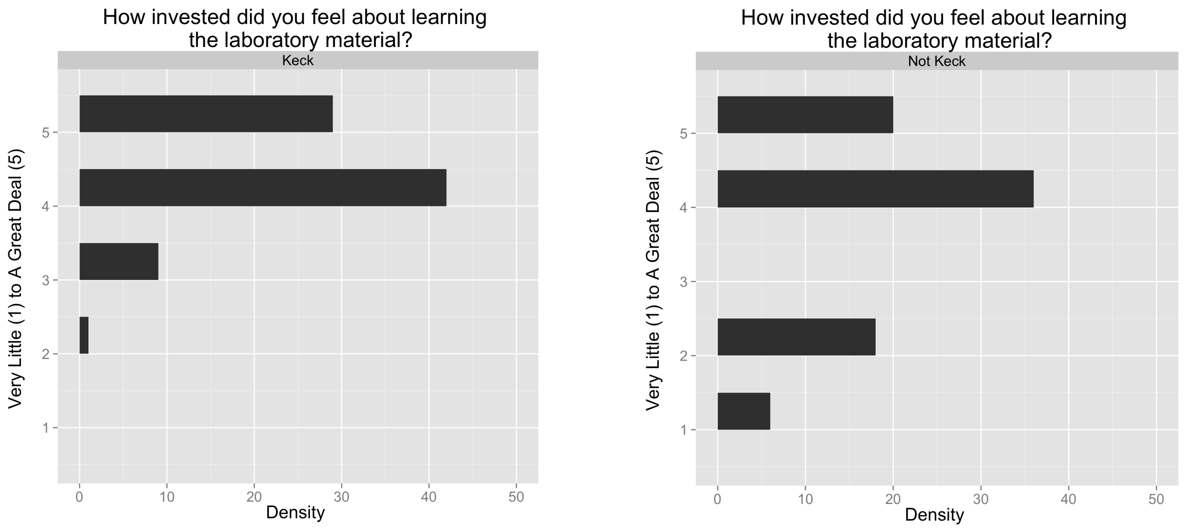
(a) (b)

Figure 3. The student responses to the question, “How much control did you have over the laboratory experiment success?” separated based on laboratory module design to be (a) open ended, and (b) existing traditional laboratory that was not modified as part of the project.

The second survey question asked the students how invested they felt about learning the laboratory material in each module. The average for this question for all the experiments was 3.67 with a standard deviation of 1.01. When separated, the laboratory modules that were designed to be open ended had an average of 4.21 with a standard deviation of 0.70. The oven module had a mean of 4.33 with a standard deviation of 1.04. The open-ended laboratory modules correlate highly with an increase in student investment in the labs. This is consistent with the faculty observations that students working in smaller groups without a “right answer” on a laboratory experiment are more engaged.

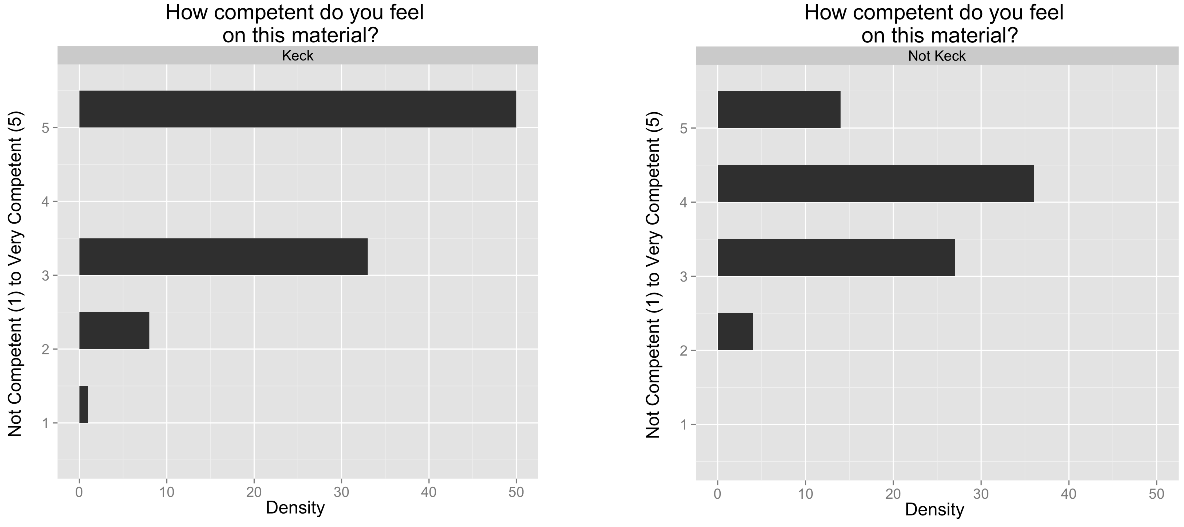
The last question on the survey asked students to rank how competent they now feel on specific learning objectives. The list-included objectives directly addressed by the new oven module, but also learning objectives tied to the more traditional laboratory modules. The results are shown in Figure 5. The average response for all the objectives was 3.91 with a standard deviation of 0.86. The responses for the learning objectives tied to the oven module were slightly higher with an average of 3.99 and a standard deviation of 0.88.

For each learning objective the students were also asked to estimate if their competence had increased. The students overwhelmingly indicated an increase in each learning objective identified with 82% reporting “yes”. For the objective targeted by the oven modules the increase in competence was 78%, slightly lower than the average for all the laboratory objectives.



(a) (b)

Figure 4. The student responses to the question, "How invested did you feel about learning the laboratory material?" separated based on laboratory module design to be (a) open ended, and (b) existing traditional laboratory that was not modified as part of the project.



(a) (b)

Figure 5. The student responses to the question, "How competent do you feel on this material?" separated based on learning objectives targeted by (a) the open ended modules, and by (b) existing traditional laboratory that was not modified as part of the project.

Conclusions

An inexpensive toaster oven has been modified to create a platform to enhance mechanical engineering student engagement through the full mechanical engineering curriculum. A set of toaster ovens was modified to allow students to control temperature and air circulation over time. The modification was flexible to allow control using different platforms.

Students in thermodynamics laboratory tested the first ovens and the educational methodology with great success. Students reported the oven module was significantly more open ended than more traditional laboratory experiments they experienced in the course. They also reported higher engagement in the open-ended experiments using the toaster oven. Independent observation by another education expert confirmed that the new experiments enhanced engagement during the student experiments.

Future work will bring the modified toaster ovens into two additional laboratory courses. A full assessment of the first group of students to pass through the sequence of courses is planned to better understand if the consistency in the equipment benefits students.

Acknowledgements

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