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Experiential Learning in the Thermal Sciences: Introducing and Reinforcing Fundamental Thermodynamics and Heat Transfer Principles to K-12 and Engineering Undergraduate Students

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Work in Progress: Experiential Learning in the Thermal Sciences - Introducing and Reinforcing Fundamental Thermodynamics and Heat Transfer Principles to K-12 and Engineering Undergraduate Students

Introduction

Over the past decade, many initiatives have been developed and published regarding innovative freshman engineering programs aimed at increasing experiential learning and promoting student success [1-4]. The primary goal of these efforts are generally to improve student understanding, confidence, performance, and retention. These programs have proven to be largely successful in achieving the desired ends and are often very popular with the student body; however, it has also been found that a significant portion of students (~20% or more) may still struggle when leaving these freshman environments and entering the more traditional engineering courses later in their curriculum [2, 5]. This may be especially true for courses centered on the thermal sciences such as thermodynamics, heat transfer, and fluid mechanics, the core concepts of which have been documented as being particularly difficult for students to grasp [6-9].

To address this issue, a pilot program has been developed which incorporates new in-class hands-on activities, demonstrations, and teaching styles into two different thermal science courses: Thermodynamics I (sophomore year by curriculum, all engineering majors) and Heat Transfer (junior year by curriculum, mechanical engineering majors). The objectives of this pilot program are to 1) introduce and reinforce fundamental thermal science concepts via experiential learning, 2) evaluate the effectiveness of these efforts on improving student understanding and performance, 3) reduce the number students requiring repeated attempts to pass thermal science courses, and 4) adapt select activities from the pilot program to be leveraged across multiple K-12 age ranges as part of science, technology, engineering, and math (STEM) outreach activities.

To date, this program has been in place for three academic sessions of each course. The work presented here will cover results and observations to-date, preliminary evaluations of effectiveness relative to standard (non-pilot) program instances, and plans for future work. Grade distribution, pass/fail percentage, and anonymous student feedback surveys are utilized as metrics to evaluate the impact of the pilot program's changes for each of these courses.

Description of Program

The pilot program utilizes experiential learning tools in the form of hands-on projects, classroom activities, and discovery-based teaching styles within thermal science courses as a means to *augment* rather than replace lecture material and provide a "bridge" between qualitative and quantitative learning. It also recognizes that learning styles vary between individuals [10-12] and seeks to provide complementary educational material in a variety of ways in order to maximize student understanding and success.

One challenge to implementing a more experiential approach to existing courses is the increased time required for each activity versus traditional lecture. Thus, instructors must balance removing topics, faster pace of lecture, and increasing semester credit hours and/or contact hours with the potential benefits of such a program. In this study, the existing Thermodynamics I course was worth three semester credit hours which typically relates to 3.75 contact hours per week within a quarter system. However, to accommodate the interactive and hands-on activities this class is currently scheduled for 5.5 contact hours per week within a quarter system. Conversely, the junior level Heat Transfer class (which is also worth three semester credit hours) retains its 3.75 contact hours per week, with the tradeoff being a faster pace of traditional lecture to allow time for experiential learning activities. This difference in time management between the two courses is due to a) previous hands-on activities included in Thermodynamics I being gradually phased out in years prior to pilot program without changes to scheduling, b) slower pacing necessary in lower-level engineering classes compared to upper-level courses, and c) the ability to substitute conceptual experiential problem solving for certain hands-on activities in Heat Transfer versus Thermodynamics I. Specific pilot program activities and elements utilized thus far are described below, with some simplified versions being utilized for local K-12 STEM outreach initiatives as well.

Activity: Thermal transport in heat pipes (phase change system) versus solid copper rods (simple conduction)
Description: Students experience first-hand how a heat pipe performs relative to a solid copper rod when both are exposed to the same temperature difference. The participant holds the copper rod in one hand and the heat pipe in another, then places the ends of each in an ice bath simultaneously and observes which becomes cool to the touch faster (Figure 1). The heat pipes and copper rods were obtained from Educational Innovations, Inc.
Example Discussion Questions: Based on our discussion of heat pipe fundamentals, explain in words from an engineering perspective what happened during the experiment. What role did your hand and the heat from your body play in relation to the heat pipe's operation? What role did the ice bath play? If instead of an ice bath we used a cup of hot water, what would you expect your observations to have been? Based on your observations, explain in words from an engineering perspective what you think would happened during such an experiment. What role would your hand play in relation to the heat pipe's operation? What about the hot water?
Class(es): Thermodynamics I, Heat Transfer, and K-12 STEM outreach
Concepts Covered: Latent heat, evaporation, condensation, conduction

Figure 1. (*Left*) Thermodynamics I students experience the capabilities of a heat pipe versus a solid copper rod. (*Right*) A simplified version of this same activity being performed by elementary school-aged participants at a Society of Women Engineers Future Engineers Day event.

Activity: Infrared thermometry/thermal imaging
Description: This activity illustrates the use of infrared thermal imaging as a tool to visualize temperature differences and facilitates discussion of its fundamental operating principles. Students experience first-hand how thermal imaging can give fast, qualitative, and quantitative information regarding temperature gradients and potential sources of thermodynamic irreversibility. Discussion also centers on the limitations of such methods in terms of accuracy and the need to compensate for surface emissivity. In practice, a thermoelectric cooler and hot plate serve as hot and cold items of interest which the students can use as focal points of a hand-held commercial IR camera (Figure 2). Besides observing temperature differences according to scaling, the students are also instructed to point the camera at an isothermal room temperature area and observe how rescaling skews the perceived temperature differences. Following this, a small box fan is placed near the hot plate and the reduction in temperature due to forced convection is visualized and discussed. Finally, aluminum and copper heat sinks of similar geometry are placed on the hot plate to facilitate visualization and discussion of how differences in surface emissivity can affect quantitative IR temperature measurement. IR visualization was accomplished via FLIR E4 compact thermal imaging cameras.
Example Discussion Questions: Based on our discussion of surface emissivity and the fundamental operating principles of IR thermometry, explain why such tools require calibration for the specific surface whose temperature is of interest for measurement. What would happen if the surface's emissivity were lower (higher) than that expected by the instrument?
Class(es): Thermodynamics I (irreversibilities) and Heat Transfer (temperature gradients, radiation, emissivity, convection)
Concepts Covered: Temperature, temperature gradients, temperature measurement, radiation, emissivity, conduction, convection

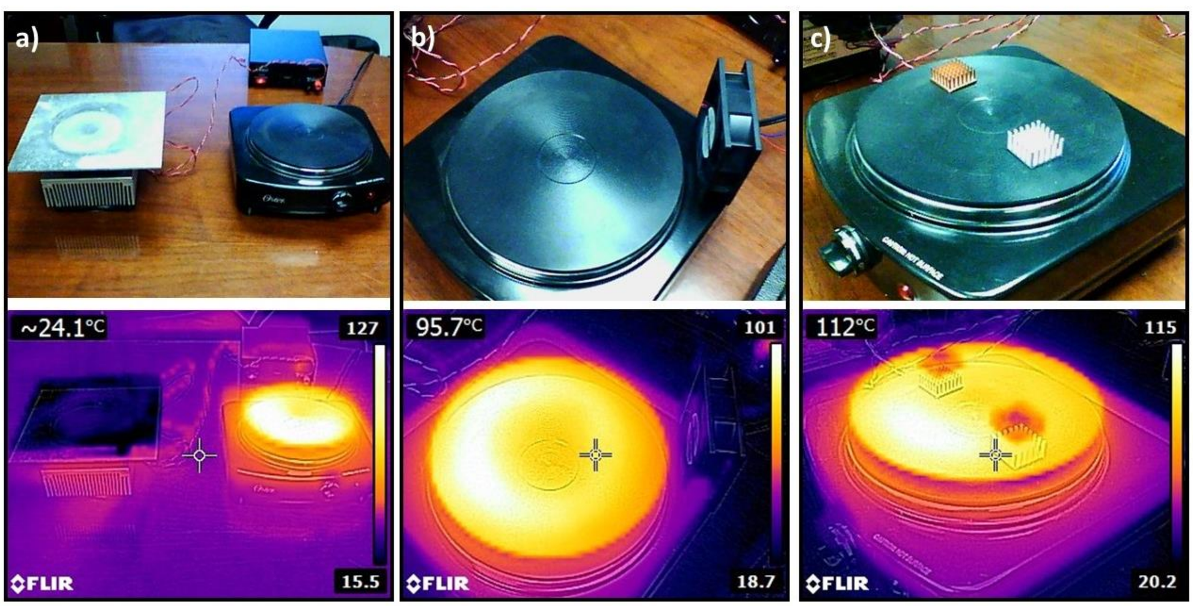


Figure 2. a) A thermoelectric cooler and hot plate are used as focal points for visualizing hot and cold surfaces/temperature differences, with the associated IR thermal image given below the visual spectrum analogue. b) A box fan is placed in close proximity to the hot plate to visualize the effect of forced convection. c) Copper and aluminum heat sinks of similar geometry are imaged while in contact with the hot plate to illustrate how surface emissivity affects IR thermometry readings.

Activity: Miniature steam engine
Description: A miniature steam engine (Figure 3a) is used as an in-class demonstration by the instructor to illustrate the large amounts of energy that steam can store and how it can be converted to useful forms of mechanical work. The steam engine was obtained from Jensen Steam Engines.
Example Discussion Questions: What kinds of useful applications can be facilitated by the rotating shaft work output of the steam engine (electrical power generation, transportation, etc.)? Based on the heat input and work output, what is the thermodynamic First Law efficiency of this particular steam engine? What are some ways in which that efficiency might be improved?
Class(es): Thermodynamics I
Concepts Covered: Steam energy, steam engines, shaft work, First Law efficiency

Activity: Boyle's Law experimental confirmation
Description: Students work in groups with a piston-cylinder setup to measure air pressure within the cylinder as the volume is increased or decreased at constant temperature (Figure 3b). Oil from a reservoir is used in place of a piston to prevent leaks at the periphery. Students then compare their observed results with those predicted by the ideal gas equation of state at constant temperature (i.e. Boyle's Law). Setup is a TD1000 model obtained from TecQuipment.
Example Discussion Questions: Make an X-Y plot with volume as the x-axis and absolute pressure on the y-axis. Add a power law trendline and give its equation either on the plot. According to the Ideal Gas equation of state, what SHOULD the exponent in this equation be? How closely does the exponent for your data compare to the theoretical value (% difference)? Comment on how close (or far) your data was from being in agreement with the pressure/volume behavior predicted by Boyle's Law. List potentially causes of error or uncertainty in the experiment. Under what conditions would you expect ideal gas behavior to not be observed?
Class(es): Thermodynamics I
Concepts Covered: Ideal gas equation of state/Boyle's Law, piston-cylinder devices

Activity: Internal combustion engine operation
Description: Students work in groups with manually operated, unlabeled cutaway models of gas and Diesel engines (Figure 3b). These engine models move through their respective operating cycles as a hand crank is turned by the student, thereby allowing them to control how quickly or slowly the model progresses. Based on the discussion in class of the fundamentals of internal combustion engines and their own observations of the models, students must determine which model is a gas engine and which is a Diesel engine as well as determining if these engines operate on two- or four-stroke cycles. The cutaway models were obtained from Eisco.
Example Discussion Questions: Which of the two models (labeled A and B) depicts a gasoline engine and which a Diesel engine? How do you know? Is Model A a two-stroke or a four-stroke engine? What about Model B? How do you know? If we model the gasoline engine using the ideal Otto cycle operating using air and with a compression ratio of 8, what is its thermal efficiency? If we model the Diesel engine based on its ideal cycle operating using air using a compression ratio of 12 and a cutoff ratio of 2, what is its thermal efficiency?
Class(es): Thermodynamics I and K-12 STEM outreach
Concepts Covered: Ideal versus actual thermodynamic cycles, quasi-equilibrium states, Otto cycle, Diesel cycle, two-stroke and four-stroke internal combustion engines

Figure 3. a) A miniature steam engine used as an in-class demonstration. b) Students performing the Boyle's Law activity. c) Manually operated cutaway models of gas and Diesel engines used to facilitate visualization and discussion of their operating principles.

Activity: Magdeburg plates
Description: This is a simplified version of the historically well-known Magdeberg hemispheres apparatus used to demonstrate vacuum versus atmospheric pressure. Here, two plastic plates with grooves cut for a rubber o-ring seal take the place of the hemispheres for simplicity but the operating principle and discussion elements are the same. After the two plates are placed together with the o-ring, a small hand pump is used to pull a vacuum in the space between them. The level of the vacuum is measured using a manual vacuum gauge and is recording by the students, who work in groups. Based on the vacuum level, students are then tasked with determining the absolute pressure within the enclosure and, based on its size, the amount of force that would be required to pry the plates apart. For safety reasons, they are clearly instructed NOT to attempt this act. This activity is especially well suited to illustrate the concepts of gage, absolute, and vacuum pressure which can be quite confusing for some Thermo. I students and which become critical later on in the course. Hence, this is typically the first activity performed within the class. Magdeburg plates were obtained from Pasco.
Example Discussion Questions: What is the vacuum pressure between the plates in inches of Hg, kPa, and psia? What is the absolute pressure between the plates in inches of Hg, kPa, and psia? What force in pound-force (lbf) and in Newtons (N) is required to pull the plates apart?
Class(es): Thermodynamics I
Concepts Covered: Absolute pressure, gage pressure, vacuum pressure, units

Teaching Style: "Heat transfer intuition"
Description: Throughout the academic term, the instructor repeatedly speaks to the students about utilizing their lifetime of observations and experiences regarding thermal energy - i.e. "heat transfer intuition" - when working problems or trying to understand new concepts from an engineering perspective. The goal here is to link their prior engrained memories, day-to-day interactions, and experiential knowledge with the more technical concepts, scientific principles, and problem solving methodologies being introduced during lecture. Besides working to tie together new information with existing knowledge, this teaching methodology is also conducive to working with topics not readily able to be easily or safely conducted by large numbers of students within a classroom.
Example Discussion Questions: When your food is too hot and you blow on it to accelerate its cooling, why does this work? Based on the concepts introduced in class today, can you explain

why this happens in terms of hydrodynamic and thermal boundary layers? When you're cooking and need to move a hot pan or lid, what kind of material do you use to protect your hand from burns? Describe why a potholder is effective in terms of thermal conduction resistance based on our lecture. On a summer's day, air can be seen to be rising off the surface of hot asphalt. What is the source of heat to the asphalt and what phenomena is causing the air above it to be in motion? Is this an example of forced or natural convection?
Class(es): Heat Transfer
Concepts Covered: conduction, convection, radiation,

Measures of Effectiveness

The primary objective of the program is to improve student success and understanding in thermal science courses by introduction and reinforcement of fundamental thermal science concepts via experiential learning. If successful, the most direct outcome would be a measurable reduction in the number of undergraduate engineering students having to repeat thermal science courses and improved progression towards graduation. Measures of effectiveness utilized in this work include anonymous student surveys, statistical evaluation of student grades, and comparison of the pilot program's outcomes to those of conventionally-taught sections of the same course. All student surveys and the use of grade information have been approved by the appropriate Institutional Review Board (documentation available upon request).

Results to Date

For Thermodynamics I, a grade of C or better is required for the student to receive curriculum credit for the course and move on to higher-level thermal science classes. Hence, for the statistical analysis of grades, the percent of students who pass is similarly defined by those achieving a C or better. Grading was on a fixed ten point scale with no curve applied. The same instructor taught the pilot program offering each time, while two other instructors led the standard course offerings.

Results for the past seven non-summer academic sessions (in this case, quarters) are shown in Table I below, with each offering indicated as being either pilot or non-pilot (standard) and placed in chronological order from left to right. Averages for both types are shown on the far right. Based on the average enrollment of the pilot program (45 students), the single-student resolution of the stated percentages is approximately 2.2 %. As can be seen, the average percent of students passing the pilot program offerings is 6.9 % higher than standard offerings, with the effective class GPA being comparably higher as well (6.3 %). This is largely due to a higher (lower) percentage of students earning Cs (Ds) in the pilot program than in the standard course. However, the percentage of students dropping the course during the terms is essentially the same between the two (28.9 % for pilot, 32.1 % for standard) compared to the single-student resolution of the data. In terms of pilot program development and improvement over time, the percentage of students dropping the course has remained almost constant across the three offerings to date. Over those same offerings, however, the percentage of students passing the course has steadily risen from 51.4 % to 60.0 %.

Table I. Student grade data for pilot program and standard offerings of Thermodynamics I over past seven academic sessions.

	Pilot 1	Standard 1	Standard 2	Pilot 2	Standard 3	Standard 4	Pilot 3			
Grade (Quantity)										
As	5	6	7	5	10	10	6			
Bs	7	17	19	9	14	11	13			
Cs	6	12	19	13	19	5	11			
Ds	3	6	16	2	5	8	4			
Fs	4	7	6	6	8	4	2			
Course Dropped	10	26	20	15	31	20	14			
Total Enrolled	35	74	87	50	87	58	50	**Avg. (Pilot)**	**Avg. (Standard)**	**Diff.**
Grade Percentages								**Grade Percentages**		
As	14.3%	8.1%	8.0%	10.0%	11.5%	17.2%	12.0%	12.1%	11.2%	0.9%
Bs	20.0%	23.0%	21.8%	18.0%	16.1%	19.0%	26.0%	21.3%	20.0%	1.4%
Cs	17.1%	16.2%	21.8%	26.0%	21.8%	8.6%	22.0%	21.7%	17.1%	4.6%
Ds	8.6%	8.1%	18.4%	4.0%	5.7%	13.8%	8.0%	6.9%	11.5%	-4.7%
Fs	11.4%	9.5%	6.9%	12.0%	9.2%	6.9%	4.0%	9.1%	8.1%	1.0%
Course Dropped	28.6%	35.1%	23.0%	30.0%	35.6%	34.5%	28.0%	28.9%	32.1%	-3.2%
Percent Pass (C or better)								**Percent Pass (C or better)**		
	51.4%	47.3%	51.7%	54.0%	49.4%	44.8%	60.0%	55.1%	48.3%	6.8%
Effective Class GPA								**Effective Class GPA**		
	2.24	2.19	2.07	2.14	2.23	2.39	2.47	2.29	2.22	0.06

A voluntary, anonymous online survey administered at the end of the course (after the drop date) was provided to the students to provide feedback on the pilot program's effectiveness in enhancing understanding. This resulted in a 76 % response rate amongst those enrolled. Respondents identified themselves as 80 % male, 20% female. Race identification was 80 % white, 4 % Black/African American, and 16 % Asian. In terms of age, 32 % of respondents were 18 to 20, 56 % 24 to 26, and 12 % 24 to 26. No student identified as having a disability.

Survey results show significant student support and positive qualitative feedback regarding depth of understanding and interest in thermal science subjects. Of the activities described above, students cited the thermal imaging activity as their favorite, with the Boyle's Law being a close second. The Magdeburg plates activity was widely regarded as the least engaging. Respondent responses to specific survey questions are shown in Figures 4-6 below, followed by a selection of representative student comments.

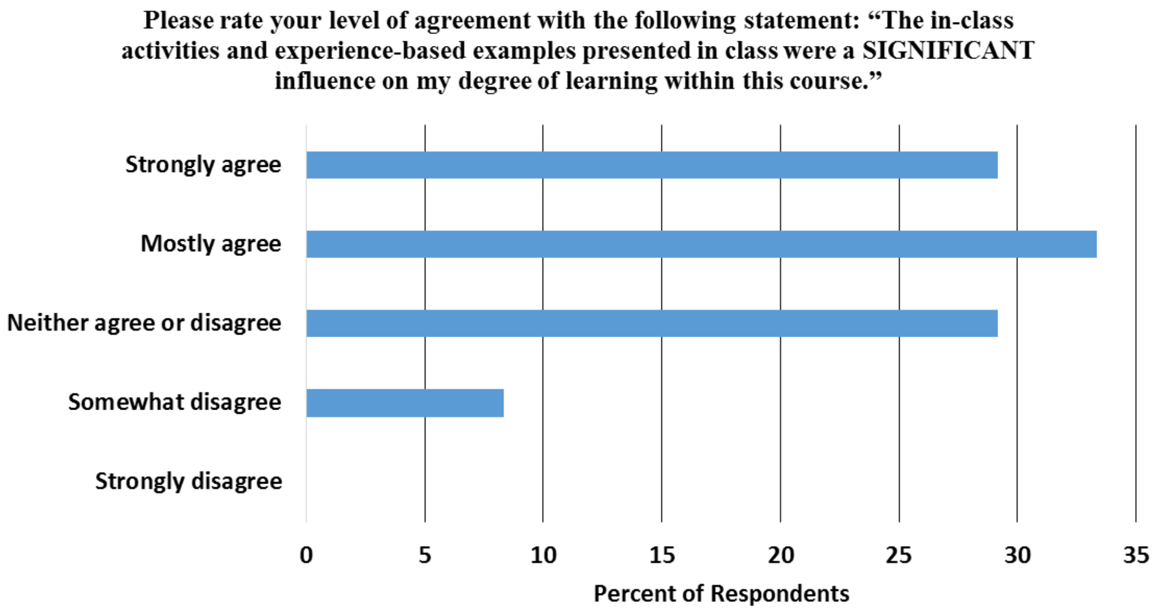


Figure 4. Student responses to anonymous survey question regarding relative impact of experiential activities on their degree of learning.

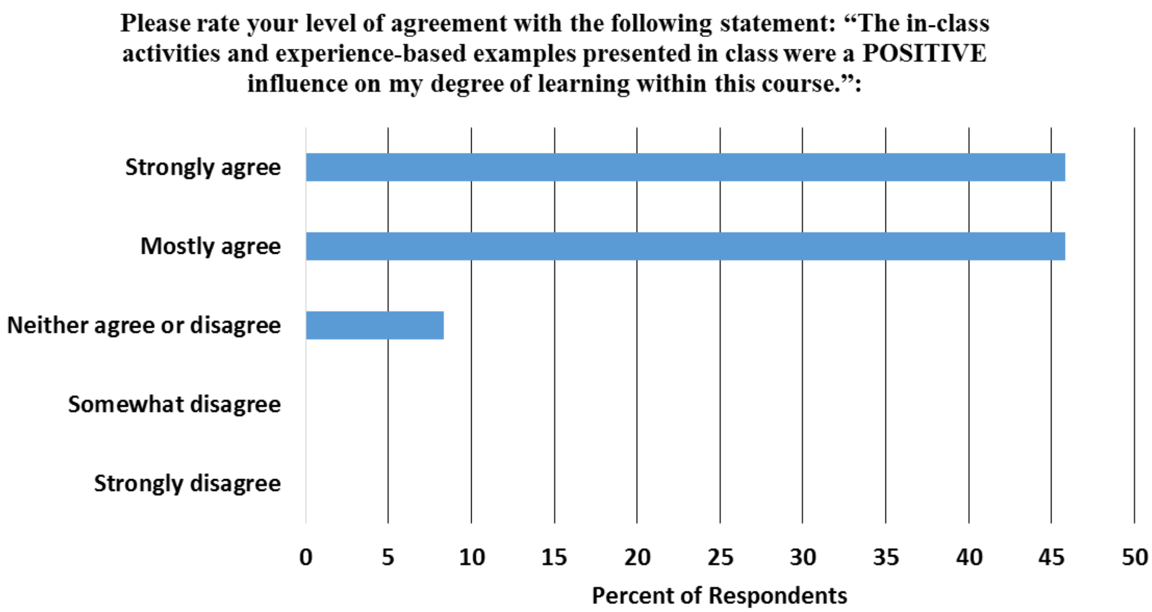


Figure 5. Student responses to anonymous survey question regarding influence of activities on their degree of learning.

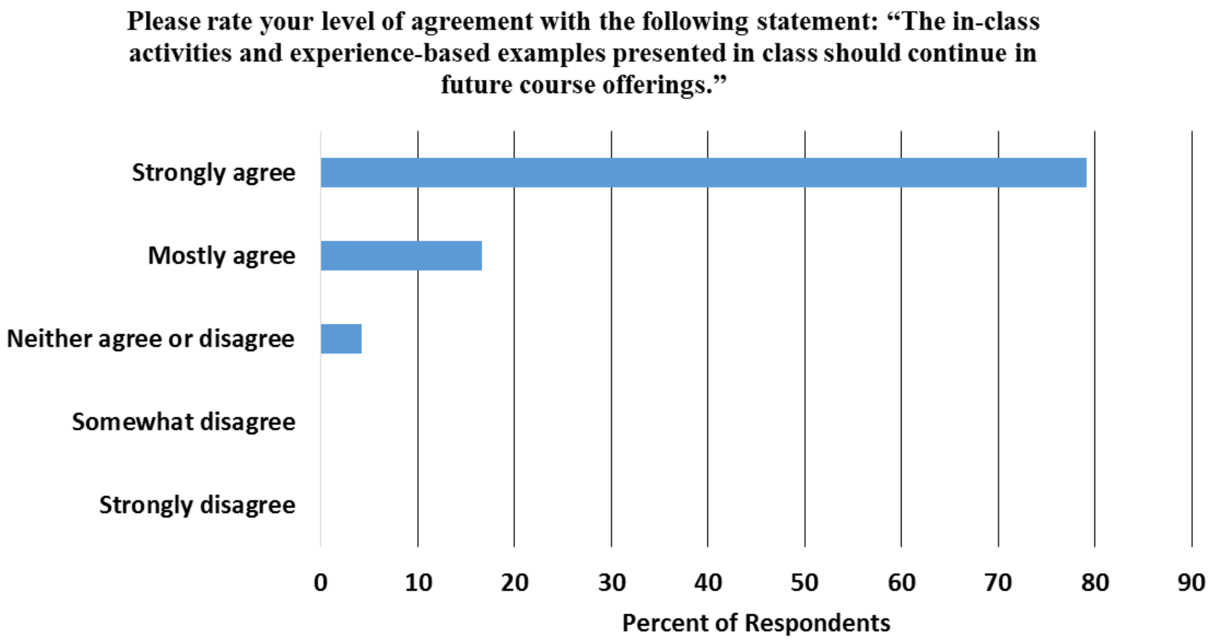


Figure 6. Student responses to anonymous survey question regarding whether this type of program should continue.

Question: Which in-class activity was your favorite and why?
"The Boyle's Law activity because it was fun to do an actual application of our lectures."
"The thermal imaging lab was my favorite because we learned some practical applications for thermal imaging devices, which I found quite interesting."
"Engine cycles lab was my favorite. I always wanted to know how an engine works in a vehicle and this lab gave that insight to me and I learned a lot about the process and the differences between the 2 cycles analyzed."
"I really enjoyed the Boyle's Law activity. It was the most involved and hands on project we did."
"The thermal imagining activity, it was a fun activity that stimulated my interest."

Question: Which in-class activity was your least favorite and why?
"My least favorite was the Boyle's Law. It was interesting to see but does not pertain as much to daily life and is used more in the solution of a problem than a tangible part that is used."
"Pressure lab was the least favorite. This lab didn't seem to help me get a good practical idea about the uses of gage pressure and actual pressure in real world."
"The Pressure activity, just the most boring one."
"Pressure vacuum lab, took a long time and I don't feel like it aided my understanding."
"I disliked the thermal imaging lab least because it did not seem to be very accurate to me."

For Heat Transfer, a grade of D or better is required for the student to receive curriculum credit for the course and move on to the highest-level thermal science classes. Hence, for the statistical analysis of grades, the percent of students who pass is similarly defined by those achieving a D or better. Grading was on a fixed ten point scale with no curve applied. The same instructor taught the pilot program offering each time, while another other instructor led the standard course offerings.

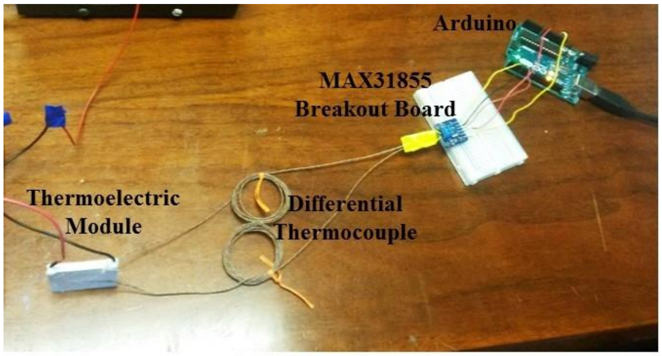
Results for the past seven non-summer academic sessions (in this case, quarters) are shown in Table II below, with each offering indicated as being either pilot or non-pilot (standard) and placed in chronological order from left to right. As of the writing of this paper, a third pilot program instance of Heat Transfer is underway but final data is not yet available. Averages for both program types are shown on the far right. Based on the average enrollment of the pilot program (31 students), the single-student resolution of the stated percentages is approximately 3.2 %. As can be seen, the average percent of students passing the pilot program offerings is 5.3 % higher than standard offerings. The effective class GPA for the pilot program was substantially higher (2.36 vs 1.92). This is due to a higher percentage of students earning B’s and C’s in the pilot program and fewer D’s and F’s than in the standard course. The percentage of students achieving A’s or dropping the course remained with the single-student statistical resolution between the two offering types.

Table II. Student grade data for pilot program and standard offerings of Heat Transfer over past seven academic sessions.

	Standard 1	Standard 2	Standard 3	Standard 4	Pilot 1	Pilot 2	Standard 5			
Grade (Quantity)										
As	1	4	1	3	1	3	1			
Bs	6	5	9	5	8	11	5			
Cs	11	17	11	9	10	15	15			
Ds	19	25	22	7	1	4	3			
Fs	12	10	8	2	1	0	6			
Course Dropped	6	11	4	4	3	5	9			
Total Enrolled	55	72	55	30	24	38	39	**Avg. (Pilot)**	**Avg. (Standard)**	**Diff.**
Grade Percentages								**Grade Percentages**		
As	16.2%	1.8%	5.6%	1.8%	10.0%	4.2%	7.9%	7.1%	6.7%	0.4%
Bs	16.2%	10.9%	6.9%	16.4%	16.7%	33.3%	28.9%	25.0%	15.9%	9.1%
Cs	32.4%	20.0%	23.6%	20.0%	30.0%	41.7%	39.5%	35.8%	27.1%	8.7%
Ds	13.5%	34.5%	34.7%	40.0%	23.3%	4.2%	10.5%	13.8%	26.7%	-12.9%
Fs	13.5%	21.8%	13.9%	14.5%	6.7%	4.2%	0.0%	5.4%	12.8%	-7.3%
Course Dropped	8.1%	10.9%	15.3%	7.3%	13.3%	12.5%	13.2%	12.9%	10.9%	2.0%
Percent Pass (D or better)								**Percent Pass (D or better)**		
	67.3%	70.8%	78.2%	80.0%	83.3%	86.8%	61.5%	85.1%	79.8%	5.3%
Effective Class GPA								**Effective Class GPA**		
	1.29	1.48	1.47	2.00	2.33	2.39	1.73	2.36	1.92	0.45

Planned Future Work

The primary needs for this program are a) more data by which to make conclusive statements regarding effectiveness, b) deeper understanding of differences in instructor, time of year, and class size, and c) continual improvement of its experiential aspects. Based on this preliminary data, current plans call for continuing the experiential learning pilot programs with continual improvement efforts and additional data gathering/analysis. Improvement efforts refer specifically to refining existing activities as well as developing new ones. One example of such an activity under development is shown in Figure 7. This involves characterizing the power consumption and cooling capacity of a small thermoelectric cooler which students can then perform an energy balance on to determine its thermodynamic efficiency. As an adding learning/integrated curriculum aspect, the temperature measurements associated with this project are performed via an Arduino-controlled thermocouple amplifier (MAX31855) which can be used for either single or differential thermocouple operation (Figure 7). In this way students also learn principles of temperature measurement via thermocouples as well as data logging via Arduino and its associated coding. This activity is intended to integrate across the Arduino-based projects often found in freshman curriculum classes as well as basic measurements/instrumentation courses that are part of most engineering curricula.



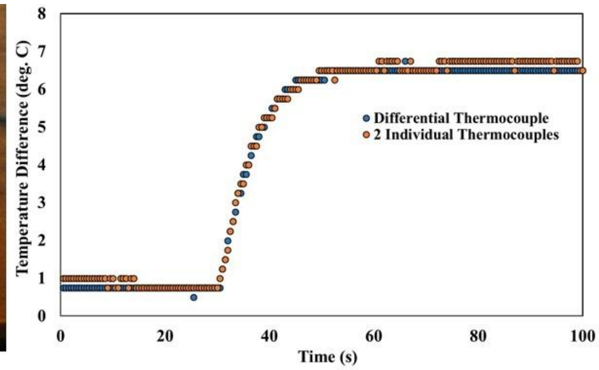


Figure 7. (*Left*) Developmental setup using an Arduino module and breakout board along with a differential thermocouple to measure the temperature difference across a small thermoelectric module. (*Right*) The obtained temperature data over two runs: once with the differential thermocouple and another using two individual thermocouples. Temperature resolution as set by the amplifier is 0.25 ^{o}C.

Conclusion

Collectively, the results to-date suggest measurable but modest gains in student pass percentages with the pilot program but no significant drop in the percentage of students dropping the course. More promising is the increase in students earning the required grade of C rather than a D in Thermodynamics I, which may indicate the experiential teaching elements are helping marginal students move across the passing mark and be able to progress towards a degree without having to repeat the course. The increase in effective class GPA for Heat Transfer may also be seen as a positive outcome, though that class also showed no measurable change in students dropping the course. However, these are not conclusive findings due to the small number of students that have presently participated in the pilot program. In addition, these straightforward statistics do not yet account for variance in instructor, time of year taught, and other factors. Thus, while early results are promising further work is required before conclusive findings can be drawn, including continual program improvement.

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