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A Mixed Methods, Longitudinal Evaluation of Problem-Based Learning and Inquiry-Based Activities in a Heat-Transfer Course and Lab

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Abstract

This paper describes 10 years of pre/post assessment data from a heat transfer course taught using problem-based learning and an accompanying laboratory course that utilized both traditional and inquiry-based activities. Both the course and lab are required for third-year students completing the mechanical engineering concentration and are taught annually at a small liberal arts university.

Each year, students completed the Heat and Energy Concept Inventory (HECI), hosted online at the AIChE Concept Warehouse, as both a pre- and a post-test for the course. Statistically significant differences were found between the pre/post mean responses for the complete inventory as well as the inventory's content areas. In addition, statistically significant differences between pre/post mean responses in a given year are considered in light of any substantial changes to the course material and/or structure.

In addition to the quantitative results, selected comments from the corresponding class' Senior Survey, which students completed one year after finishing the heat transfer course, are discussed. Student comments indicated the course structure was a challenging way to learn but helped them improve their approach to independent learning and working in groups. In addition, students expressed increased confidence in working on complex, open-ended problems.

Introduction and Background

George Fox University is a small, Christian, liberal arts university located in Newberg, OR. The engineering program at George Fox offers a B.S. in Engineering with concentrations in biomedical, civil, computer, electrical, and mechanical engineering. ENGM 380 Heat Transfer (HT) is a required course for students completing the mechanical engineering concentration and is taught annually in the Spring. Students typically take the course during their third-year in the engineering program. In Spring 2024, 30 students were enrolled in HT.

In Spring 2009, the instructor began teaching a heat transfer course using a traditional, lecture-based pedagogy. During the following years, the instructor both heard from other faculty and witnessed how electrical engineering students were better prepared to handle the open-end problems encountered during Senior Design projects. One electrical engineering course in particular (ENGE 420 Embedded Systems Design, taught by Dr. Gary Spivey) seemed to be the main contributor to student confidence and competence in handling the complexity and challenges of an open-ended problem with a long time frame.

In October 2012, the instructor attended the first ever National Effective Teaching Institute 2 (NETI-2) workshop which was held in Seattle, WA. While NETI-1 provides "instruction and hands-on practice in the elements of effective teaching," NETI-2 is for "STEM instructors who are already familiar with the topics of NETI-1 and are looking for more advanced active learning strategies to engage students at a higher level" [1]. During the Workshop, Dr. Michael Prince from Bucknell University, a co-leader of the workshop, shared his experience of using a problem-based learning approach in his heat transfer course for several years and offered to share his course materials with those that were interested. The author requested the materials from Dr. Prince and then used them to implement problem-based learning in his heat transfer course.

The instructor's shift to problem-based learning (PBL) was motivated by both the experience with electrical engineering students (discussed previously) and by the purpose of PBL—using problems to drive student learning. By providing students with problems relevant to the next topic in a course, students gain context and motivation for the instruction. The PBL experience is active [2]. In the case of this study, the instructor's role is most often a "guide on the side" rather than a "sage on the stage." This approach to PBL where the instructor is actively engaged in the learning process is in contrast to using PBL as a pure discovery learning activity [3], [4].

As an additional layer to the PBL framework, since students work on teams to solve problems *and* team members are accountable for their own understanding of the assignment, this application of PBL also incorporates cooperative learning [5]. Thus, the in-class student experience for the course in this study shifted from a mostly individual experience of listening to a lecture and completing an example problem or two to engaging with teammates, asking questions where more understanding was needed, and, when the instructor did lecture, listening and thinking about how the content applied to the problem they were trying to solve.

The instructor also learned about CATME Peer Evaluations [6] at NETI-2, which has been used to assess the teaming experience in HT. Using CATME's online rubric interface, students can evaluate their teammates. Once the data is released by the instructor, CATME provides students with feedback on how their peers evaluated them along with suggestions on how to improve. When setting up an evaluation, the instructor can choose to allow students to provide open-response feedback that only the instructor can see. The instructor first used CATME in a Fluid Mechanics course in November 2012 and has continued to have students complete a CATME survey in a variety of courses both during and after almost every team-based activity.

Soon after the instructor's NETI-2 experience, he learned of inquiry-based activities that were being developed by Prince et al. to correct student misconceptions of heat transfer concepts [7]. They provided a description and a validation of these activities in their 2016 paper. They identified four misconception areas and then developed two activities for each area:

- Temperature vs. Energy: 1) Crushed vs. Block Ice, 2) Melting Ice Simulation
- Temperature vs. Perceptions of Hot and Cold: 1) Water Bath Activity, 2) Human Thermometer
- Rate vs. Amount: 1) Liquid Nitrogen, 2) Adiabatic Valve
- Radiation: 1) Polished and Painted Steam Pipes, 2) Heat Lamp

The inquiry-based activities were attractive due to the availability and low cost of materials, the relatively short amount of time needed to both perform the experiment and complete predictions and reflections, and the (then preliminary) research indicating the effectiveness of the activities to correct student misconceptions. The instructor incorporated these activities into a laboratory course (details provided below).

Assessment Instruments

In order to assess the impact of the change to a PBL pedagogy and the addition of inquiry-based activities, this paper reviews 12 years of student comments from the engineering program's Senior Survey as well as 10 years of pre/post student responses to a concept inventory.

Each year, a week or two before graduation, senior engineering students are emailed a link to the Senior Survey. Since students typically take the heat transfer course in their third year, their responses to the survey typically come one year after the end of the course. The survey collects information about students' post-college contact information, job or grad school prospects, assessment of ABET Outcomes and Performance Indicators, as well as ratings of various campus services and facilities. The survey concludes with some open-ended responses. Responses to the prompt "Of the engineering professors at George Fox University, which several were the most influential in your professional development and why?" that reference the instructor or HT from 2010–2023 are discussed below.

In addition, from an ASEE Educational Research and Methods Division email in late 2012, the instructor learned about the Heat and Energy Concept Inventory (HECI), which was being developed by Prince et al. [8]. The HECI developers were requesting help with the validation phase of the inventory. When applying to be a part of the study, the instructor learned about the AIChE Concept Warehouse [9], one of places where the inventory was being hosted. The HECI used eight questions that were either taken directly or modified from the Thermal and Transport Concept Inventory (TTCI) [10]. The TTCI includes concepts from thermodynamics, fluid mechanics, and heat transfer while the HECI focuses on just heat transfer. In addition, the TTCI does not include radiation concepts while the HECI does. The HECI contains 36 questions across the same four misconception areas itemized above for the inquiry-based activities. Three questions from the HECI are shown in Figures 1 and 2 by permission since they have already been published in [8].

The results and discussion of this study help to illuminate not only what concepts students may start the course knowing, but they also provide evidence for how a problem-based approach may enable students to learn certain concepts. By comparing when significant differences in concept understanding occurred relative to changes to the course and supporting courses, we identify interventions that enhance student learning.

The next section provides a more in-depth background into the instructional history of the heat transfer course as well as courses that support its content. We also present the pedagogy and identify when assessment tools are used in the course. The data from the HECI is then presented. The overall results for each instrument and its content areas are identified and discussed in light of the course content and pedagogy. Comments from the Senior Survey are then presented followed by a discussion of the results along with the limitations and implications of this study.

Question 29: A flat sheet of aluminum foil and a thicker aluminum baking sheet are placed in an oven at 400°F for a long period of time. While holding these objects from the oven, which feels hotter to the touch?

a. Both objects feel equally hot because they are at the same temperature
b. The baking sheet feels hotter because it is hotter
c. The aluminum foil feels hotter because it is hotter
d. The baking sheet feels hotter because it has a higher mass

Figure 1: Question #29 (Temperature vs. Perception) from the HECI [8].

Steam at 100°C is fed into 2 metal pipes, otherwise identical except that one is painted with a flat black paint while the other pipe has a shiny copper finish. You may assume that radiation is a significant fraction of the total heat flux from the pipes to the surrounding room and that the rate of heat loss from the pipes determines how fast the steam condenses.

Question 9: In which pipe will steam condense at a faster rate?

a. Steam will condense more quickly in the shiny copper pipe
b. Steam will condense more quickly in the painted black pipe
c. Steam will condense in both pipes at equal rates

Question 10: Because…

d. The paint acts as an insulator
e. The black paint absorbs and holds in the heat better
f. The polished surface will reflect heat better
g. Black paint has a higher emissivity
h. The exterior color does not matter

Figure 2: Questions #9 and #10 (Radiation) from the HECI [8].

Current Course Structure

The thermal fluids courses prior to HT in the ME curriculum include Engineering Thermodynamics, which students typically take the spring prior to HT, and Applications of Engineering Thermodynamics and Fluid Mechanics, which students typically take the semester prior to HT. Except for 1-3 students each year, all the students enrolled in Heat Transfer take ENGM 381 Energy Lab the same semester. The current structure of HT and ENGM 381 Energy Lab are provided below along with previous iterations of both courses.

ENGM 380 Heat Transfer

HT is a 3-credit hour course taught on Tuesdays and Thursdays in 1 hour and 15 minute time blocks. The four-week homework schedule is shown in Table 1.

Prior to the first day of HT, the instructor sends an email to enrolled students with a brief introduction to the course, information about the textbook, and requests them to complete both the CATME Team-Maker [6] and HECI surveys. On the first day of the course, students receive handouts that discuss expectations for an algorithm submission, the first two homework problems, and an outline of the course. The instructor introduces the PBL learning cycle via a general outline of how an introductory lecture, algorithms, and homework reports support learning prior to a quiz or exam. Students then learn who their team members are, which were informed by the CATME Team-Maker responses and the instructor's experience with the students the previous semester. In the time that remains, the instructor provides an introductory lecture on heat transfer and steady-state conduction.

The homework problems that the students will solve are open-ended such that the students will need to clarify the criteria for the solution. In addition, the problem statement provides some data that are relevant to the solution process as well as some data that may not be included in the solution. Students are expected to complete research and identify what information is useful and what is not. They may also make appropriate assumptions. For example, for the first homework cycle, students size a dialysis filter. Since there are several aspects of the filtration process that involve transient mass diffusion, students are told that assumptions can be made to simplify the problem to a state-state analysis. Yet, at the same time, they need to both justify their assumptions and discuss how those assumptions impact their final results. Unlike most textbook homework problems, students must identify and justify multiple assumptions and learn how to handle ambiguity.

In order to support students' problem solving, each student must write up an algorithm for the problem by the end of the second week. The algorithm is a written plan for how they envision solving the problem. It includes a statement of the problem, a sketch of the physical system with

Table 1: Four-week schedule for one cycle of homework problems in ENGM 380 Heat Transfer.

Week		In Class	Due at Start of Class
1	Tu	Course Intro & Lecture (Cycle 1)	Concept Inventory, CATME Team-Maker
	Th	Start HW1, HW2	25 Questions for HWs 1&2 (team)
2	Tu	Work day	Team Contract (team; bring hardcopy)
	Th	Review Algorithms, Work day	Algorithms 1 & 2 (individual)
3	Tu	Work day	
	Th	Discuss HW Problems	HWs 1&2 due (team)
4	Tu	Quiz 1 / Lecture (Cycle 2)	CATME Peer Eval (individual)
	Th	Start HW3, HW4	Team Reflection (HWs 1&2), 25 Questions for HWs 3&4 (team)

each relevant mechanism of heat or mass transfer identified and labeled, a list of what they know is relevant to the solution, a series of equations, and a list of assumptions (along with their justifications) that are needed to solve the problem. Since each student submits their own algorithm, it is expected that the algorithms from a given team will look very similar, but the individual submission provides accountability that each student is at least writing up a plan and starting to think deeply about each problem.

Before the second class in the learning cycle, students are told to work with their teams to come up with 25 questions for each problem by the start of the next class (a reduced version of a 100 question Q-storm session [11, pp. 154–155]). They must also submit one of those questions for each homework problem a day prior to the class. The instructor develops a response to each question and during the second class, discusses the students' submitted questions. Sometimes the instructor might provide a direct answer; sometimes the instructor will ask for clarification and/or ask what the students think about what a question is asking. With the remaining class time, students work in their groups and complete their team contract, which is due at the next class. The team contract helps the team to reflect on past teaming experiences and set expectations for their current team.

The following week, students have work days when the instructor moves from team to team to help out and direct their work. During this week, the instructor invites students who have already completed HT to come back and talk with the current students. They could be a senior(s) who completed the class and/or a graduate(s) who indicated the value of the course structure to their learning. (The instructor started inviting former students after a graduate from the first PBL iteration returned for a graduate panel session. When the panel was asked, "Which class do you use the most in your work?" this graduate responded that Heat Transfer was the most valuable course but not because he uses any of the content from the course. It was because the PBL pedagogy helped him learn how to solve open-ended problems and learn new things.) When the former students come to class, the instructor briefly introduces the senior and/or graduate, then leaves the room until a student indicates they are done. By leaving the classroom, the instructor hopes that students feel less inhibited about asking questions about the course structure or about the instructor. The instructor still does not know what questions have been asked or what answers have been given during this time.

The algorithms are due at the start of the fourth class in the cycle. During this class, the instructor starts by using a random number generator to select both the teams and the team member that will present their algorithm. Teams are given about 10 min to draw their sketch and list equations on the whiteboards. After each team presents, the instructor allows for questions from other teams and provides feedback. These presentations are another opportunity for students to demonstrate their struggle with the learning process, which provides a natural opportunity for the instructor to correct or direct the entire class in the solution process.

In the third week, class time is devoted to "work days" to develop a final solution and write up the homework reports. A single homework report for each problem is submitted by each team. The class is provided with a report template that provides the headings that the instructor expects as well as a brief discussion about the content that should be in each section. The students also have access to the grading rubric that is used to evaluate the reports. By writing up their solutions in a report format, students must organize their knowledge and demonstrate their process for learning the material for the homework problem. On the day the students submit their homework reports, the instructor shares their approach to solving the problem. In addition, depending on the homework problem, the instructor asks each team for key values from their solution to a problem. The values can then be compared and students can discuss how their different assumptions and solution approaches may have caused the differences. At the end of the class, the instructor reminds students about a review sheet, which itemizes the expected content knowledge students can anticipate needing for the quiz/exam.

At the beginning of the fourth week, students take the quiz/exam. Students have 35 min to complete a quiz and the entire class period (1 hr 15 min) to complete an exam. The quiz/exam starts with some of the concepts that were itemized on the review sheet. For quizzes, the second part asks students to demonstrate the solution process for a specific part of each of the homework problems. For exams, students are asked to develop a complete algorithm for one of the homework problems or a problem very similar to a homework problem. The quizzes and exams provide individual accountability for understanding since the homework report was a team submission.

Around the time of the quiz/exam, students are expected to complete a CATME Peer Evaluation [6] of their team members. Because students are at a certain level of mental exhaustion after a quiz, the instructor does a brief introduction to the content needed for the next set of problems and finishes early so students have time to work on their Team Reflection. Teams work through a set of questions that prompt them to identify where they were successful in the previous homework cycle and where they could improve. The homework cycle then starts over at the next class.

The composition of teams remains the same for two cycles, which is after the first exam. The instructor then changes the teams based on how students engaged during the first half of the course. Another CATME Team-Maker survey may be used.

Previous Iterations of ENGM 380 Heat Transfer

Prior to the switch to PBL, the course was taught via a lecture and worked examples in class and assigned textbook homework problems to be completed outside of class. The assessments for the course included four exams and a Final Exam. A laboratory component, discussed below, was incorporated into the course grade.

Since Spring 2013, the instructor has asked students to complete the HECI via the AIChE Concept Warehouse [9] platform both at the start and at the completion of HT. Unfortunately, in the instructor’s haste to have HT students complete the inventory as a pre-test for the Spring 2013 semester, the instructor assigned students to complete the heat transfer portion of the Thermal and Transport Concept Inventory [10]. Noticing this error, the instructor then assigned the HECI for the post-test. The instructor incentivized these students to complete the HECI with the following: “You should have just received an email about completing [a concept inventory]. If you complete it, I will increase your overall course grade by 1%.” For all subsequent attempts at the HECI, the instructor has only asked students to complete the inventory and sent reminders; no incentives were offered.

Since Spring 2014, the PBL version of the course has gone through minor iterations which included adding or changing homework problems. For example, a dialysis filter design problem was not taught until 2017 and the radiation problems changed from a solar water heater analysis to problems involving analyzing a vacuum insulated bottle and the impact of shielding on a thermistor.

ENGM 381 Energy Lab

The development of ENGM 381 Energy Lab (EL) is discussed here due to its significance in supporting and reinforcing the learning happening in the heat transfer course. During the first two weeks of EL, students complete the inquiry-based activities (discussed above) for Temperature vs. Energy, Temperature vs. Perception of Hot and Cold, and Rate vs. Amount. The week following the misconception labs, students complete experiments focused on thermocouples and the refrigeration cycle along with completing a thermal analysis tutorial using ANSYS Mechanical. In Week 4, students complete experiments that take the entire lab time (Bomb Calorimeter, Conduction through a Tapered Rod, and Major/Minor Losses) and require a more traditional lab write-up. The following week they do peer review on their write-ups with submissions due the following week. This cycle repeats two more times for each of the laboratory teams (which are different from the HT teams) to complete each of the main experiments. The students then complete a Cooking Lab where they cook a roast, apple, and potato while monitoring their temperatures with thermocouples. In addition, they model the food in SOLIDWORKS and develop a transient thermal simulation in ANSYS Mechanical. For the final two weeks of the course, the students explore drag on spheres in the wind tunnel and complete the two Radiation inquiry-based activities.

Previous Iterations of ENGM 381 Energy Lab

In 2013, the labs that now make up the EL were embedded in two separate courses: ENGM 312 Applications of Thermodynamics (AoT, a fall course that students take the semester before HT) and the heat transfer course. In Fall 2012, the AoT lab experiments consisted of the following: Temperature and Pressure measurement, Bomb Calorimeter, Engine Analysis, Venturi, Refrigeration, and Saturation Temperature and Pressure. The Spring 2013 Heat Transfer labs were a tutorial on how to complete a thermal analysis using SOLIDWORKS Simulation, Conduction through a Tapered Rod, Heated Cylinder in Cross-flow, Lumped Capacitance, Force Convection through a Heated Pipe, Natural Convection over a Vertical Plate, Cooking Lab, and Radiation/Natural Convection of Copper Pipes.

After each lab meeting, students were expected to submit individual reports by the following week, which consisted of an introduction, procedure, results, discussion, and conclusion. In Fall 2013, the AoT labs remained unchanged while the inquiry-based activities (except for the Radiation activities) were taught for the first time as part of the Spring 2014 HT labs. Students still completed the SOLIDWORKS Simulation tutorial and the Cooking Lab. Instead of completing the other labs, students worked in teams to upgrade the experimental apparatuses used previously with new materials as well as refine the lab handout for the experiment.

The instructor was on sabbatical during the 2014-15 academic year. All of the instructors' courses and labs were either canceled or taught by an adjunct instructor. For the courses that were canceled, the instructor either taught a larger section or had two sections of a course the following year.

In the transition to combining the AoT and the HT labs into EL, the AoT lab was dropped from the course in Fall 2015. When the HT lab was taught for the final time in Spring 2016, it consisted of the inquiry-based activities, most of the previous (but now upgraded) experiments, and a new "Freestyle" lab where students choose a common object, analyze how they interact with it, and complete a thermal analysis of the object using SOLIDWORK Simulation.

In Spring 2017, EL was taught for the first time. The lab experiences that were incorporated from the AoT and HT labs were the inquiry-based activities (except for the Radiation activities), Temperature and Pressure measurement, Refrigeration, SOLIDWORKS Simulation tutorial, Bomb Calorimeter, Conduction through a Tapered Rod, Natural Convection over a Vertical Plate, Major/Minor Losses (experiment added this year), Drag on Spheres (a wind tunnel experiment added this year), Force Convection through a Heated Pipe, Freestyle Lab, Cooking Lab, Lumped Capacitance, and Radiation/Natural Convection of Copper Pipes.

In Spring 2018, students completed the Radiation inquiry-based labs for the first time, which replaced the Lumped Capacitance and Radiation/Natural Convection of Copper Pipes experiments. Since 2018, the lab experiences in EL have remained relatively constant except for the following:

- Spring 2020 (COVID): student did not complete the Drag on a Sphere or the Cooking Lab. Also, instead of physically performing one of the Radiation inquiry-based activities, they watched a video of the instructor completing the activity.
- Spring 2021:
    - Students completed both of the Temp. vs. Perception activities and one of Rate vs. Amount activities (Melting Ice Simulation) at the beginning of the semester.
    - Students completed the second Rate vs. Amount activity (Crushed vs. Block Ice) and both of the Temp. vs. Energy activities in Week 13. This change only occurred this year.
    - Switched to completing thermal studies in ANSYS Mechanical rather than SOLIDWORKS Simulation. This change has continued to the Present.

Results

The gender and ethnicity demographics of students who responded to more than 18 of the 36 questions on the HECI are shown in Tables 2 and 3. These students took the PBL version of the course from 2014–2023.

Table 2: Gender demographics for students who answered more than 18 questions of the HECI from 2014–2023.

Gender	Pre-Test *N = 200*	Post-Test *N = 150*
Male	82.5%	81.3%
Female	17.5%	18.7%

Table 3: Ethnicity demographics for students who answered more than 18 questions of the HECI from 2014–2023.

Ethnicity*	Pre-Test *N = 200*	Post-Test *N = 150*
White	82.0%	82.7%
Asian	4.5%	3.3%
Hispanic	3.0%	4.7%
Multiracial	6.0%	4.7%
No response	3.0%	2.7%

* 1 student self-identified as Black or African American, 1 student as Nonresident Alien, and 1 student as Native Hawaiian

HECI Analysis

A summary of the pre and post-test results is shown in Table 4 and discussed in detail for each targeted concept area in the following sections. The text of the HECI questions are not included to preserve the confidentiality of the test. However, example questions from the HECI can be found in the developers' paper [8], and the entire HECI may be obtained by either contacting the HECI developers or creating an account at the Concept Warehouse website [9]. In addition, since the developers' grouped questions Q24 and Q29 with both Temp. vs. Energy and Temp. vs. Perception, the same has been done for this study.

Reviewing the number of respondents who answered more than 18 questions, the decrease from pre-test to post-test respondents was nearly 50% in 2018, 2020, and 2023. It is unclear to the instructor why there was a low response rate in 2018; students did complete all of the misconception lab write-ups via the Concept Warehouse website, which may have led to fatigue and burnout. In late March of Spring 2020, the class moved to Zoom-only instruction due to COVID and the instructor only asked students to take the survey at the end of Finals Week (end of April). The instructor does not have a hypothesis for why the response rate was low in 2023.

Table 4: Mean pre and post-test performance data by content area for each year and overall.

			Total		Temp. vs Energy		Temp. vs Perception		Rate vs Amount		Radiation	
Year	**Pre n**	**Post n**	**Pre x̄ (SD)**	**Post x̄ (SD)**	**Pre x̄ (SD)**	**Post x̄ (SD)**	**Pre x̄ (SD)**	**Post x̄ (SD)**	**Pre x̄ (SD)**	**Post x̄ (SD)**	**Pre x̄ (SD)**	**Post x̄ (SD)**
2013		16		23.2 (6.4)		6.1 (1.7)		5.8 (1.7)		4.7 (2.6)		7.5 (2.4)
2014	16	15	18.6 (4.7)	25.3 (4.8)	6.2 (2.3)	7.5 (1.5)	5.5 (2.0)	7.1 (1.5)	2.9 (2.0)	5.4 (1.5)	5.1 (1.6)	6.8 (2.8)
2016	18	14	20.1 (6.2)	22.7 (7.6)	6.3 (1.7)	6.1 (2.7)	5.7 (1.5)	6.0 (2.1)	3.5 (2.2)	4.6 (1.9)	5.5 (2.7)	6.9 (3.0)
2017	34	33	20.6 (5.7)	21.6 (5.4)	5.6 (2.0)	6.2 (2.0)	6.2 (1.5)	6.2 (1.7)	5.3 (2.1)	4.3 (1.8)	4.5 (2.3)	5.9 (2.4)
2018	27	15	17.7 (6.4)	26.7 (3.5) **	5.3 (2.0)	7.5 (1.5)	5.6 (2.3)	7.1 (1.1)	3.3 (2.5)	5.9 (1.1) *	4.4 (2.1)	7.8 (2.1) **
2019	25	21	18.8 (5.8)	23.9 (6.2)	5.3 (2.1)	6.3 (2.5)	5.6 (2.1)	6.7 (1.4)	4.0 (2.6)	5.4 (1.8)	4.8 (2.2)	6.6 (3.3)
2020	24	7	18.8 (7.0)	24.1 (3.6)	5.9 (2.5)	6.1 (1.6)	4.8 (2.1)	6.1 (1.6)	4.2 (2.4)	5.1 (2.3)	4.7 (2.1)	7.6 (2.1)
2021	25	18	20.0 (6.9)	28.1 (4.4) **	6.1 (2.0)	7.6 (1.8)	5.6 (2.0)	7.1 (1.4)	4.0 (2.1)	5.7 (1.6)	5.0 (2.8)	8.7 (2.2) **
2022	18	19	16.8 (6.7)	25.7 (7.1) **	5.6 (2.1)	6.8 (2.1)	5.6 (2.4)	6.9 (1.7)	2.4 (2.2)	5.4 (2.3) **	4.3 (2.5)	7.9 (2.6) **
2023	13	8	19.3 (4.8)	25.0 (5.5)	5.8 (1.4)	6.6 (1.6)	6.0 (1.8)	7.0 (1.4)	3.3 (2.3)	4.0 (2.4)	5.2 (1.6)	8.6 (1.6)
Overall	200	150	19.1 (6.1)	24.5 (5.9) **	5.7 (2.1)	6.7 (2.1) **	5.6 (2.0)	6.7 (1.6) **	3.8 (2.4)	5.1 (1.9) **	4.8 (2.3)	7.2 (2.7) **

* = $p < 0.05$

** = $p < 0.01$

Repeated measures ANOVA showed that the Overall mean scores for the entire inventory ("Total") as well as each content area changed significantly:

- Total: $F(1, 199) = 72.357$, $p < 0.001$, $\eta 2 = 0.168$
- Temp. vs. Energy: $F(1, 199) = 20.298$, $p < 0.001$, $\eta 2 = 0.055$
- Temp. vs. Perception: $F(1, 199) = 27.895$, $p < 0.001$, $\eta 2 = 0.074$
- Rate vs. Amount: $F(1, 199) = 30.121$, $p < 0.001$, $\eta 2 = 0.074$
- Radiation: $F(1, 199) = 85.409$, $p < 0.001$, $\eta 2 = 0.192$

A TukeyHSD was used to identify significant differences between pre/post-tests for each year. In addition, an arbitrary 70% threshold is highlighted in the plots (darker horizontal line) and heat maps (white part of gradient) of Figures 3–10 in order to identify satisfactory response rates. In order to aid comparison, Figures 3, 5, 7, and 9 have a similar format as figures from [8].

Total

While the Overall Total mean increased significantly, Table 4 shows that yearly means only increased a significant amount in 2018, 2021, and 2022. The post-test mean in 2014 and 2023 was near the 70% threshold ($\bar{x} = 25.2$).

Temperature vs. Energy

While the Overall mean for this content area increased significantly, Table 4 shows there was no significant change on a year to year basis. Reviewing the results for specific questions in Figure 3, students did show significant improvement in performance on four out of the ten questions in the content area. All of the questions that were directly addressed by a misconception lab showed significant improvement, yet, only Q30 improved significantly beyond the 70% threshold. While students did not significantly improve their response rate to Q13, Q16, and Q31, the post-test mean was greater than the 70% threshold. From year to year in Figure 4, Q06, Q14, and Q29 show the most variation in post-test mean. For example, for Q29 in 2016, the post-test mean was 0.31 while in 2018 it was 0.93.

Temperature vs. Perceptions of Hot and Cold

The Overall mean for this content area also increased significantly, but there was no significant change on a year to year basis (Table 4). The Overall results for each question in this content area are shown in Figure 5. Student performance significantly improved for five out of the nine questions in the content area; of these five questions, only Q24 did not improve beyond the 70% threshold. Questions directly addressed by a misconception lab showed significant improvement. From year to year in Figure 6, Q12 and Q29 show the most variation in post-test mean, where the post-test mean for Q12 is around 0.48 or lower for 2017, 2019, and 2020 but back up to around 0.70 in other years.

Rate vs. Amount

In addition to the Overall mean for this content area increasing significantly, Table 4 indicates that student responses in 2018 and 2022 increased significantly. The Overall results for each question in this content area are shown in Figure 7, which shows that student performance significantly improved for five out of the eight questions in the content area. Of these five questions, Q22 was the only question with a post-test correct response rate (68.7%) below the 70% threshold. A misconception lab directly addressed Q01–Q04, yet Q03 and Q04 did not show significant improvement. Figure 8 shows relatively consistent post-test means from year to year for each question.

Radiation

In addition to the Overall mean for this content area increasing significantly, Table 4 indicates that student responses in 2018, 2021, and 2022 increased significantly. The Overall results for each question in this content area are shown in Figure 9. Student performance significantly improved for seven out of the 11 questions in the content area. While the correct response rate for Q10, Q27, and Q28 increased by over 40%, their post-test mean was still below the 70% threshold. Questions directly addressed by a misconception lab showed significant improvement. Figure 10 shows that, beginning around 2018, Q09, Q10, Q27, and Q28 show a consistent shift to post-test means greater than the 70% threshold.

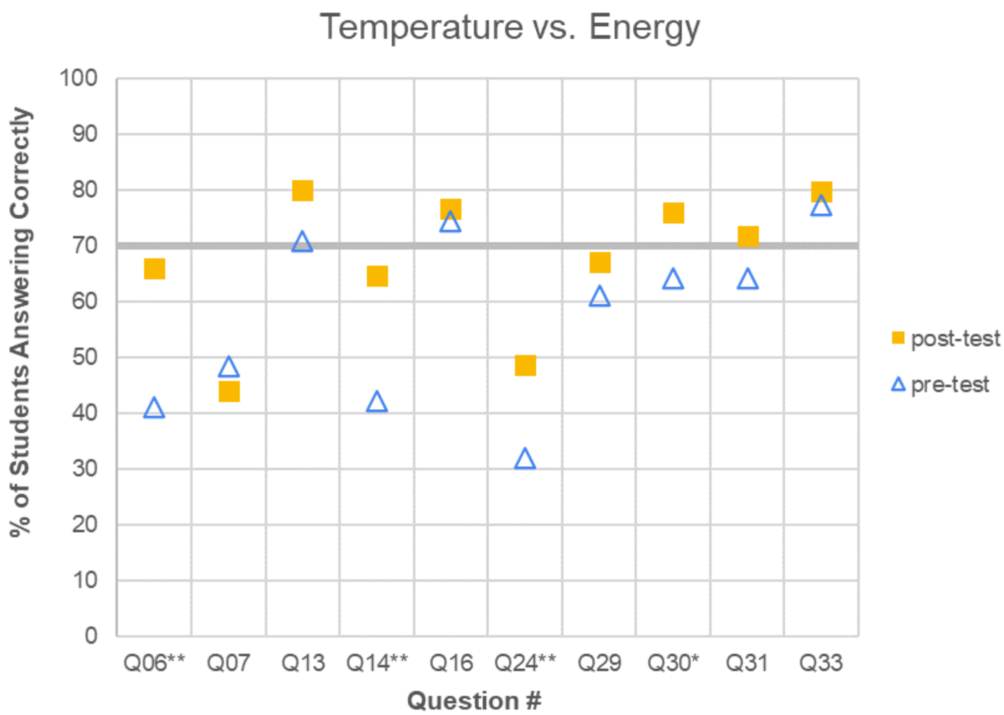

Figure 3: Mean pre/post-test % correct for Temperature vs. Energy HECI Questions
** indicates significant improvement from pre- to post-test at the $p < 0.01$ level.

Test	Year	Q06	Q07	Q13	Q14	Q16	Q24	Q29	Q30	Q31	Q33
postTest	2013	0.25	0.50	0.88	0.69	0.81	0.25	0.56	0.63	0.63	0.88
preTest	2014	0.69	0.57	0.64	0.29	0.43	0.36	0.86	0.86	0.71	0.79
postTest	2014	0.80	0.36	0.80	0.60	0.67	0.73	0.80	0.93	0.93	0.87
preTest	2016	0.44	0.71	0.78	0.61	0.83	0.44	0.56	0.61	0.72	0.67
postTest	2016	0.54	0.54	0.85	0.46	0.69	0.46	0.31	0.62	0.54	0.77
preTest	2017	0.24	0.48	0.74	0.39	0.85	0.38	0.67	0.53	0.56	0.79
postTest	2017	0.55	0.47	0.76	0.61	0.70	0.27	0.70	0.76	0.64	0.78
preTest	2018	0.30	0.48	0.59	0.37	0.59	0.22	0.70	0.63	0.63	0.78
postTest	2018	0.73	0.53	0.60	0.87	0.93	0.67	0.93	0.67	0.67	0.93
preTest	2019	0.28	0.52	0.76	0.44	0.76	0.24	0.67	0.46	0.46	0.79
postTest	2019	0.57	0.33	0.81	0.62	0.71	0.43	0.65	0.76	0.70	0.80
preTest	2020	0.46	0.50	0.58	0.46	0.88	0.42	0.35	0.75	0.71	0.79
postTest	2020	0.29	0.43	0.86	0.86	0.86	0.43	0.43	0.71	0.71	0.57
preTest	2021	0.56	0.32	0.80	0.48	0.80	0.32	0.42	0.76	0.84	0.80
postTest	2021	0.89	0.33	0.89	0.89	0.89	0.44	0.56	0.83	0.89	0.94
preTest	2022	0.47	0.44	0.78	0.28	0.67	0.33	0.67	0.56	0.56	0.83
postTest	2022	0.79	0.63	0.84	0.47	0.74	0.68	0.68	0.68	0.68	0.63
preTest	2023	0.57	0.40	0.64	0.36	0.77	0.15	0.77	0.77	0.62	0.62
postTest	2023	0.63	0.13	0.88	0.50	0.88	0.38	0.88	0.88	0.75	0.75

Figure 4: Heat map of annual pre/post-test means for Temperature vs. Energy HECI Questions

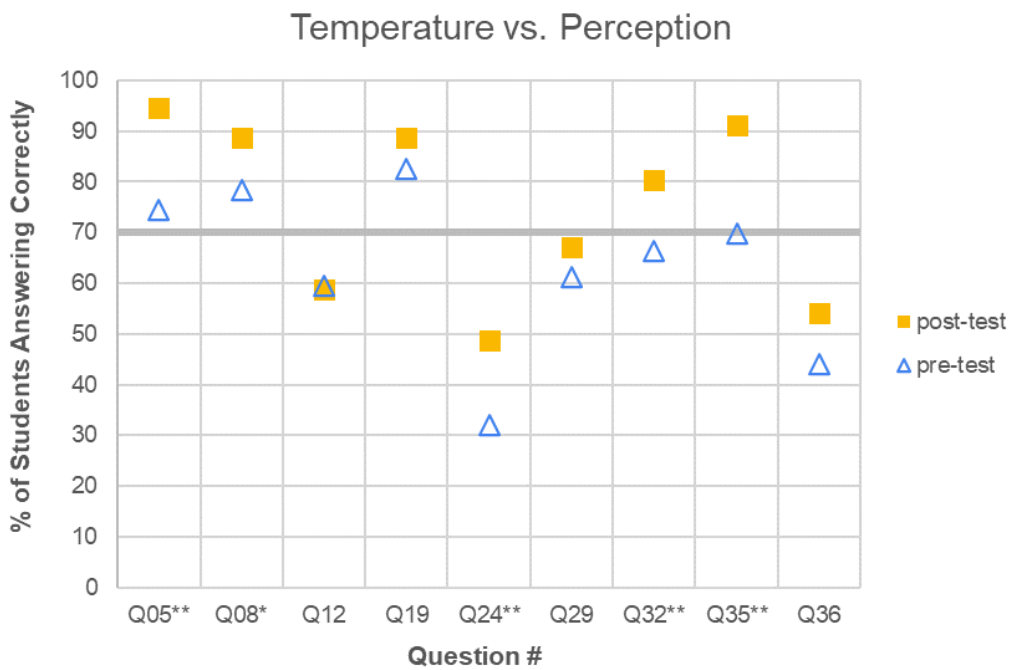

Figure 5: Mean pre/post-test % correct for Temperature vs. Perception HECI Questions
** indicates significant improvement from pre- to post-test at the $p < 0.01$ level.

Test	Year	Q05	Q08	Q12	Q19	Q24	Q29	Q32	Q35	Q36
postTest	2013	0.94	0.81	0.50	0.81	0.25	0.56	0.69	0.69	0.50
preTest	2014	0.77	0.54	0.64	0.86	0.36	0.86	0.57	0.64	0.29
postTest	2014	1.00	0.93	0.73	0.93	0.73	0.80	0.80	0.87	0.33
preTest	2016	0.89	0.89	0.72	0.61	0.44	0.56	0.67	0.72	0.22
postTest	2016	1.00	0.85	0.62	0.69	0.46	0.31	0.62	0.92	0.38
preTest	2017	0.88	0.82	0.41	0.76	0.38	0.67	0.74	0.94	0.67
postTest	2017	0.94	0.84	0.48	0.79	0.27	0.70	0.75	0.91	0.65
preTest	2018	0.67	0.81	0.74	0.85	0.22	0.70	0.67	0.56	0.37
postTest	2018	1.00	0.87	0.67	1.00	0.67	0.93	0.80	1.00	0.27
preTest	2019	0.68	0.80	0.48	0.88	0.24	0.67	0.67	0.75	0.52
postTest	2019	0.90	0.95	0.48	0.95	0.43	0.65	0.80	0.90	0.71
preTest	2020	0.67	0.75	0.42	0.83	0.42	0.35	0.50	0.63	0.29
postTest	2020	1.00	0.86	0.14	1.00	0.43	0.43	0.86	0.86	0.57
preTest	2021	0.76	0.80	0.76	0.84	0.32	0.42	0.68	0.64	0.44
postTest	2021	0.94	0.89	0.72	1.00	0.44	0.56	0.89	1.00	0.67
preTest	2022	0.44	0.67	0.72	0.89	0.33	0.67	0.67	0.67	0.61
postTest	2022	0.84	0.89	0.68	0.84	0.68	0.68	0.89	0.79	0.58
preTest	2023	0.93	0.80	0.64	0.92	0.15	0.77	0.77	0.62	0.38
postTest	2023	1.00	0.88	0.63	0.88	0.38	0.88	0.88	1.00	0.50

Figure 6: Heat map of annual pre/post-test means for Temperature vs. Perception HECI Questions

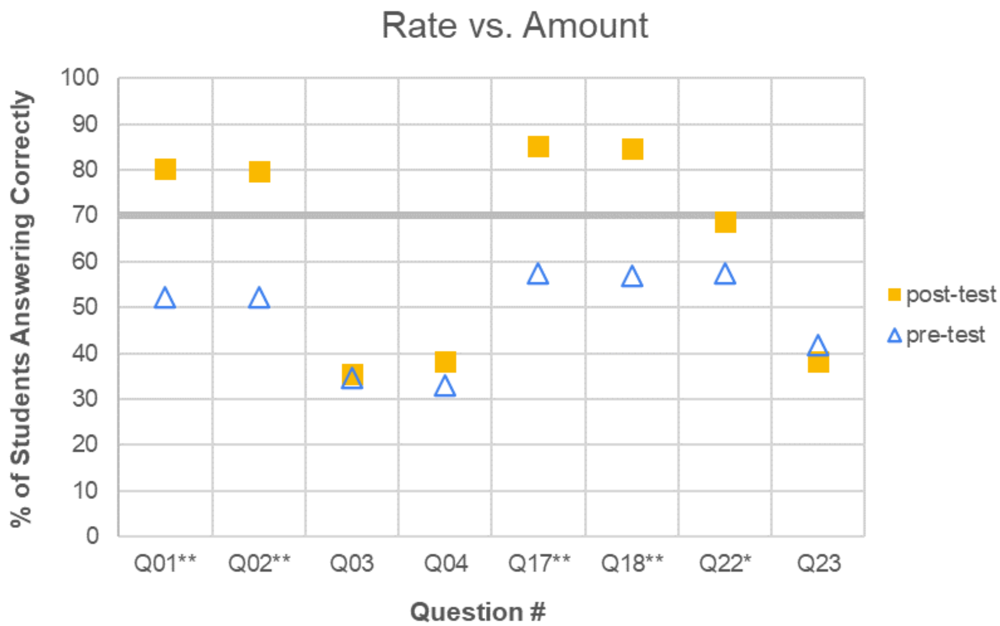

Figure 7: Mean pre/post-test % correct for Rate vs. Amount HECI Questions
** indicates significant improvement from pre- to post-test at the $p < 0.01$ level.

Test	Year	Q01	Q02	Q03	Q04	Q17	Q18	Q22	Q23
postTest	2013	0.56	0.56	0.50	0.44	0.69	0.63	0.75	0.56
preTest	2014	0.36	0.46	0.15	0.15	0.57	0.57	0.57	0.38
postTest	2014	0.79	0.86	0.27	0.40	0.93	0.93	0.87	0.47
preTest	2016	0.39	0.44	0.17	0.17	0.56	0.56	0.72	0.50
postTest	2016	0.85	0.69	0.38	0.23	0.77	0.77	0.46	0.15
preTest	2017	0.94	0.65	0.70	0.64	0.71	0.68	0.62	0.44
postTest	2017	0.73	0.79	0.21	0.24	0.85	0.79	0.52	0.15
preTest	2018	0.41	0.48	0.30	0.30	0.41	0.44	0.52	0.44
postTest	2018	0.80	0.93	0.53	0.67	0.87	0.93	0.73	0.40
preTest	2019	0.56	0.60	0.32	0.36	0.60	0.54	0.68	0.40
postTest	2019	0.85	0.85	0.30	0.40	0.90	0.90	0.86	0.50
preTest	2020	0.54	0.58	0.30	0.29	0.63	0.67	0.63	0.54
postTest	2020	0.71	0.86	0.29	0.43	0.86	0.86	0.57	0.57
preTest	2021	0.60	0.56	0.36	0.32	0.56	0.60	0.56	0.44
postTest	2021	0.94	0.78	0.33	0.39	0.94	0.89	0.83	0.61
preTest	2022	0.12	0.25	0.18	0.12	0.56	0.50	0.44	0.28
postTest	2022	0.84	0.74	0.63	0.53	0.68	0.74	0.74	0.53
preTest	2023	0.40	0.53	0.43	0.43	0.54	0.46	0.43	0.29
postTest	2023	0.63	0.63	0.25	0.13	0.88	0.88	0.50	0.13

Figure 8: Heat map of annual pre/post-test means for Rate vs. Amount HECI Questions

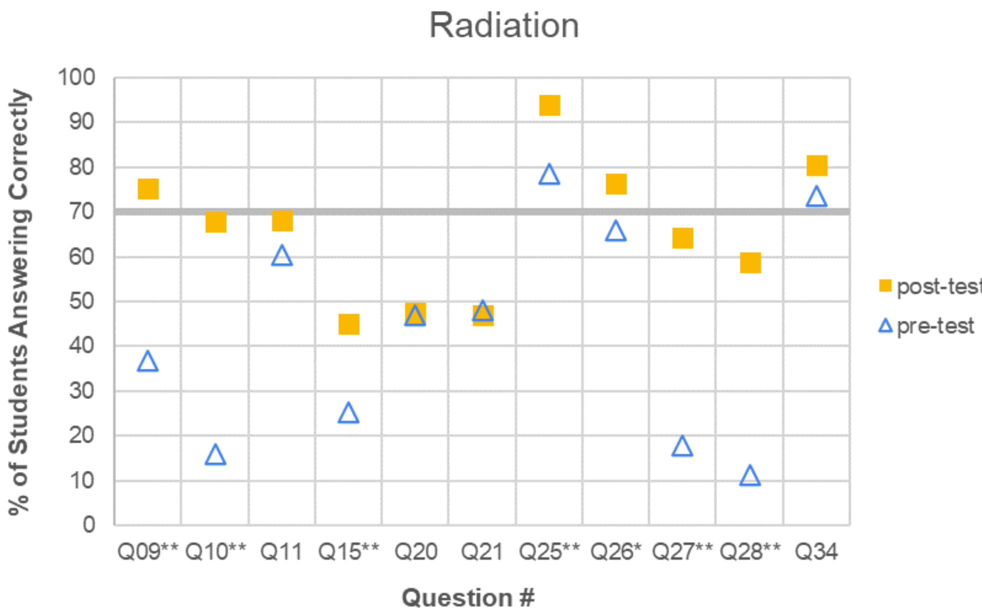

Figure 9: Mean pre/post-test % correct for Radiation HECI Questions
** indicates significant improvement from pre- to post-test at the $p < 0.01$ level.

Test	Year	Q09	Q10	Q11	Q15	Q20	Q21	Q25	Q26	Q27	Q28	Q34
postTest	2013	0.94	0.75	0.56	0.63	0.38	0.50	0.94	0.88	0.63	0.63	0.69
preTest	2014	0.46	0.07	0.71	0.43	0.36	0.36	0.86	0.79	0.23	0.14	0.71
postTest	2014	0.60	0.53	0.80	0.33	0.47	0.47	0.93	0.87	0.47	0.47	0.87
preTest	2016	0.28	0.28	0.72	0.39	0.33	0.33	0.89	0.78	0.33	0.28	0.89
postTest	2016	0.69	0.62	0.54	0.15	0.62	0.69	0.85	0.69	0.54	0.42	0.85
preTest	2017	0.35	0.12	0.73	0.15	0.35	0.38	0.79	0.71	0.18	0.09	0.71
postTest	2017	0.61	0.59	0.64	0.41	0.38	0.38	0.88	0.72	0.36	0.33	0.72
preTest	2018	0.52	0.19	0.41	0.15	0.44	0.48	0.74	0.56	0.11	0.04	0.78
postTest	2018	0.87	0.67	0.67	0.53	0.40	0.40	1.00	0.87	0.73	0.73	0.93
preTest	2019	0.28	0.28	0.60	0.13	0.68	0.68	0.76	0.67	0.08	0.00	0.78
postTest	2019	0.71	0.52	0.71	0.57	0.48	0.48	0.95	0.65	0.50	0.40	0.75
preTest	2020	0.39	0.13	0.58	0.33	0.38	0.42	0.92	0.58	0.17	0.08	0.71
postTest	2020	0.71	1.00	0.57	0.43	0.43	0.43	1.00	0.57	0.71	0.71	1.00
preTest	2021	0.40	0.16	0.56	0.28	0.64	0.60	0.68	0.68	0.21	0.16	0.64
postTest	2021	0.94	0.83	0.72	0.56	0.50	0.50	1.00	0.89	1.00	0.89	0.89
preTest	2022	0.22	0.11	0.61	0.28	0.44	0.44	0.72	0.61	0.06	0.06	0.72
postTest	2022	0.84	0.84	0.74	0.47	0.47	0.37	0.95	0.79	0.89	0.84	0.74
preTest	2023	0.43	0.07	0.50	0.38	0.54	0.54	0.69	0.54	0.38	0.31	0.69
postTest	2023	1.00	0.75	0.63	0.50	0.75	0.75	1.00	0.75	1.00	0.88	0.63

Figure 10: Heat map of annual pre/post-test means for Radiation HECI Questions

Senior Survey Comments

Every year near the end of April, students who are about to graduate are emailed a request to complete a Senior Survey. At the end of the survey are open-response questions, one of which asks, "Of the engineering professors at George Fox University, which several were the most influential in your professional development and why?" In light of what a graduate shared at a panel session about the value of the course, not for its content but for its approach to problem solving (discussed above), responses to the professional development prompt were reviewed. Students typically take HT in their third year, so most students complete the Senior Survey one year after taking the course.

The following are sample responses, edited for brevity, from 2010–2014:

- 2011 Grad - [instructor] showed a real good strength, care, and patience with us that I admired. He was always willing to help us figure out problems, which I greatly respect.
- 2013 Grad - [instructor] has been most influential to my success as an engineering student due to his many classes and effective teaching style.
- 2014 Grad - [instructor's] classes gave me a good dose of self reliance.
- 2014 Grad - [instructor] did a great job teaching the bulk of ME courses, specifically heat transfer
- 2014 Grad - [instructor] has helped me grow in seeking to be a life long learner. His approach to learning has helped me see there isn't a perfect way to do everything, so I should try my best to understand something, but not get hung up on having to perfect it. Good is good enough sometimes, greatness isn't humanly possible sometimes.

With the shift to PBL occurring in Spring 2014, the 2015 graduates were the first possible students who might mention the experience. The following are sample responses, edited for brevity, from 2015–2023:

- 2015 Grad - [instructor] was super supportive but made us learn and seek knowledge on our own. His courses were frustrating at times but he put a lot of aids…so we could learn to communicate and work together when we were struggling.
- 2015 Grad - [instructor] taught me to figure out problems for myself. I can solve problems without a book because of him.
- 2018 Grad - [instructor] encouraged us to ask questions and find the answer ourselves
- 2018 Grad - [instructor] helped me learn how I learn
- 2019 Grad - [instructor's] Heat Transfer class allowed us to tackle problems on our own and develop as engineers
- 2019 Grad - [instructor] — the variety of classes that he taught were always challenging and made me grow in my understanding of group work, working on open-ended problems and researching to find solutions
- 2020 Grad - [instructor's] courses helped me learn more about the process of problem solving with open-ended questions
- 2020 Grad - [instructor] pushed me to find new ways to learn through the different types of classes he teaches and emphasizes the importance of team skills.
- 2021 Grad - [instructor] did a good job of prepping us for the real world in Heat Transfer. It was a really hard class because of how it was structured, but it is a whole lot more real world.

- 2021 Grad - [instructor] taught me how to present information and work in teams.
- 2022 Grad - Heat Transfer was one of the hardest classes in my college career and taught me how to ask good questions and figure things out on my own.
- 2022 Grad - [instructor] helped us problem solve, form groups, learn complex material, and really wanted to help us learn.
- 2023 Grad - [instructor] encouraged a lot of development of independent learning, thinking, and problem solving.
- 2023 Grad - [instructor's] course structure prepared me well for open-ended/real-world type problems where the questions are more complicated than just choosing an equation and plugging in numbers. I think that it is largely because of [the instructor] that I have learned how to learn on the fly, so to speak, and research difficult and complex problems that require more knowledge than I currently possess.

Discussion

Except for Q03 and Q04 (Rate vs. Amount), all HECI questions that are directly related to a misconception lab show statistically significant improvement. The largest increase in mean from pre-test to post-test occurs for questions from the Radiation content area—Q09, Q10, Q27, and Q28. The large increase is likely due to the recency bias of the Radiation misconception labs occurring in the last weeks of the semester just before students completed the post-test. In addition, this increase notably began in 2018 most likely due to the addition of the Radiation misconception labs. Yet, students prior to 2018 had completed a similar radiation experiment that explored the effect of surface treatment on heating/cooling. However, the lab write-up focused on reporting rather than prediction and reflection.

Comparing the pre-test results in Figures 3, 5, 7, and 9 from this study with those from Prince, et al. [8], the pre-test results for questions from each content area are within 10% of each other except for the following: this study's mean for Q12 (Temperature vs. Perception) is ~15% lower, Q3 and Q4 (Rate vs. Amount) are approximately 20% higher, and Q15 (Radiation) is ~15% lower. Post-test means are not compared since the inquiry-based labs were likely not implemented in the Prince et al. study.

Table 5 presents the percent of students responding correctly to the HECI and its content areas. Comparing these data to mean scores from the inquiry activities test group from Prince, et al. [7], the pre-test means in this study are approximately 5% higher except for Rate vs. Amount where this study is 14.5% higher. All the post-test means are within 5% of the inquiry activities test group.

As for the comments from the Senor Survey, the following is some additional context:

- The instructor started teaching ENGM 380 Heat Transfer in Spring 2009, which was in the second year of his teaching career.
- Since 2009, the instructor has taught two required courses from the mechanical concentration (ME) in the Fall and two required ME courses in the Spring. Therefore, most ME students in their third year of the program have the instructor for one class a day.

Table 5: Pre/Post correct response mean by content area.

Content	Mean Score	
	Pre-Test *N = 200*	Post-Test *N = 150*
Temperature vs. Energy	57.3%	67.2%**
Temperature vs. Perceptions of Hot or Cold	62.7%	74.1%**
Rate vs. Amount	47.9%	63.5%**
Radiation	43.5%	65.3%**
Overall	**52.9%**	**68.1%****

** $p < 0.01$

- The instructor advised student groups in design-focused courses (a junior-level design course, called Servant Engineering [12], and Senior Design) until 2019 and 2018, respectively.

With this context, there are only a couple specific references to class work or experience prior to 2015. The instructor's experience at the time is likely a factor for why the responses are limited. However, the last two comments by 2014 graduates have a similar tone as the later comments, which could be a function of content of the senior-level courses that the instructor taught that year (Control Systems Engineering, Manufacturing Processes, and Senior Seminar).

The comments from 2015–2023 demonstrate that some students consistently value the PBL experience. Students mention experiencing independent learning, learning how to ask good questions, and understanding how to do group work well. Their comments point to increased self-efficacy toward open-ended problem solving, engaging with team members, and learning in general. Again, some of these comments may be the result of the instructor having more teaching experience in general. However, the number of specific references to the course name or to activities that only happened in ENGM 380 Heat Transfer indicate a value for PBL.

The lack of specific mentions of the PBL experience by 2016 grads is due to the instructor's sabbatical the previous year. It is unclear why 2017 grads did not reference any of the PBL experiences.

Limitations

While the data presented above compares well with previous work, the post-test may be prone to survey fatigue. Each year, students are asked or required to complete several surveys near the end of the Spring semester. This fatigue might impact the thoughtfulness that students apply to their post-test responses and to even complete the inventory. It may also explain the lack of participation in 2023.

The impact from COVID seems to be limited to the number of students who completed the post-test in 2020. With the issues surrounding the limited participation in 2023 discussed above, greater than 70% of students enrolled in 2021 and 2022 completed the HECI. In addition, responses in 2021 and 2022 were some of the only years with significant improvement.

Implications

From the perspective of improving student understanding of misconceptions in heat transfer, the implementation of the inquiry-based activities is effective. While the activities are relatively simple, they help students recognize and correct some key concepts in heat transfer. That said, the author would like to explore the impact of recency bias, if corrections to misconceptions are retained, and how to increase response rates above the 70% threshold.

The desire to explore recency bias is due to, as noted above, the response rate for three questions from the Radiation content area improving by over 40% (and Q09 improved by over 30%). Since the Radiation inquiry-based activities are performed in the last weeks of the semester to coincide with the content being covered in the heat transfer course, students had recent exposure to the inquiry activities prior to completing the post-test.

Unlike other years, students in 2021 only did both of the Temp. vs. Perception activities and one of Rate vs. Amount activities (Melting Ice Simulation) at the beginning of the semester. They then completed the second Rate vs. Amount activity (Crushed vs. Block Ice) and both of the Temp. vs. Energy activities in Week 13. Yet, the 2021 students' content area response rate was only significant for Radiation, unlike the students in 2018 and 2022 who showed significant change in their Rate vs. Amount response rate after completing both of those inquiry-based activities at the beginning of semester. However, the 2021 students' Overall response increased significantly.

As with any aspect of learning, educators hope that students will retain the knowledge and understanding that they have gained. So, do these inquiry-based activities cause lasting corrections to misconceptions? The author would like to follow up with students a year after the course, just before they graduate, to see how any misconception corrections have been retained.

While students showed significant improvement in their responses to several heat transfer concepts, there were questions where no improvement was shown. In addition, even for responses that did significantly improve, several were still below the 70% threshold. Thus, the author will be reviewing student responses on those questions to see where the misconceptions still lie in order to develop ways to correct them.

Future work will also include analyzing the results with respect to both gender and ethnicity response rates. The goal will be to identify any limitations in order to improve the response rate outcome.

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