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A Design Framework to Incorporate Problem-Solving in Engineering Teaching Labs – Case Studies for Mechanical and Thermal Fluid Topics

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INTRODUCTION

Preparing engineering students to transition from solving textbook problems to complex problems has always been a challenge in engineering education. Engineering laboratory curriculum intends for students to apply critical thinking skills to solve complex engineering problems. Students practice metacognition skills for problem-solving by identifying goals, gathering information, planning experiments to collect data, and evaluating their results (Malik et al. 2019). However, the high cost of embedding metacognitive training in laboratory experiments may often outweigh the benefits, causing universities to choose procedure-orientated instructions. In procedure-orientated laboratories, problems are laid out in a textbook format where assumptions are given, and standard solutions can be obtained by following step-by-step procedures (Burkholder E and Wieman C 2022; Holmes et al. 2017). These problems can typically be solved by employing concepts without understanding the theory or critically evaluating the situation. Additionally, many students following these procedures are unable to evaluate the validity of their solutions (Prusak, n.d.; Malik et al. 2019). As a result, these students are unprepared to solve complex, real-world engineering problems that require decomposition or knowledge transfer. (Burkholder E and Wieman C 2022; Clark and Mahboobin 2018; Prusak, n.d.).

The disconnect between classroom and real-world situations has been highlighted by educators and problem-solving skills have been emphasized in laboratory-based courses as an educational outcome. Ciocanel et al. introduced ill-structured problems to a traditional cantilever beam vibration lab and directed students to develop solutions to improve the damping of wings. Their findings indicated that students understood fundamental engineering principles better in a problem-solving lab format

than in a traditional subject-based lab (Ciocanel and Elahinia 2006). This trend continues in other fields where teaching scaffolding strategies in open-ended bioengineering projects and inquiry-based physics labs enhanced student performance and scientific reasoning skills (Clark & Mahboobin, 2018; Bransford et al., 2000). Even though positive outcomes were achieved, these teaching methods are not widespread since connecting practical applications and scientific concepts to laboratory experiments is a complex and time-consuming process (Edward 2002). Improper course design can confuse students and result in a course failing to achieve its objectives (Prusak, n.d.). A proper framework is key to successful implementation and can encourage more institutions to adopt problem-solving engineering labs. This paper documents a design framework we developed to create different mechanical engineering problem-solving lab modules. The framework offers a systematic approach for educators to strategically plan, create, and execute a series of interconnected laboratory activities spanning multiple weeks. Our methodology aims to reinforce students' understanding of previously learned engineering principles by applying them to address practical issues associated with grand engineering challenges or daily problems. This approach is designed to ignite student curiosity and encourage the application of higher-order thinking skills. The framework has been applied to two distinct fields within mechanical engineering: mechanical systems and thermal-fluid systems, both of which are presented in this paper.

Bridging the gap between academia and industry, the Department of Mechanical Engineering at Pennsylvania State University redesigned its laboratory curriculum using modern engineering topics, such as energy, sustainability, and artificial intelligence. A three-credit, fourth-year laboratory course was designed to follow a Revised Bloom's taxonomy hierarchy (Remember, Understand, Apply, Analyze, Evaluate, and Create) to improve students' metacognition skills when problem-solving (Anderson et al. 2005). This overall course design concept has been documented in our previous publication (Leung et al. 2021). This paper focuses on the detailed course design of a three-week module in the mid-semester within that larger course, emphasizing two cognitive skills: Analysis and Evaluation. The paper presents two case studies, each addressing a real-world engineering problem to capture students' interest. When registering for the course sections, students selected to participate in the thermal-fluid or mechanical systems modules. Students incorporated new techniques with their prior knowledge to complete the laboratory activities and solve these problems. Communication and practical skills were incorporated into each module, including writing effective emails and applying numerical simulations. At various stages of each lab module, we collected survey data to evaluate student perception in applying critical thinking skills when problem-solving. The majority of students felt our labs demonstrated real-world applications to the respective engineering topics across the mechanical engineering curriculum and encouraged them to apply analytical skills to solve problems.

Key words: Complex Problem-solving, Engineering Teaching Labs, Metacognitive Training

METHOD

The Educational Objective

The educational objective of our engineering teaching labs is for students to apply engineering theory to analyze real-world problems and evaluate their solutions using problem-solving techniques. Considering different decision-making techniques outlined by experts (Wankat and Oreovicz 2015; Price et al. 2021), our design emphasizes the following five techniques:

- Define a goal or criteria
- Narrow down the problems
- Identify the important information needed
- Design and implement appropriate experimentation or calculations
- Evaluate the assumptions, simplifications, and outcomes

The 1-2-3 Problem-Solving Lab Framework

This framework is for a three-week module. Each week, we focus on one of three main concepts, 1-Introduce, 2-Connect, and 3-Solve, in two 50-minute lectures and one three-hour laboratory class. A central question is selected to connect theories to a real-world engineering problem which kindles student interest and inspires curiosity. There are three conditions guiding the selection of the central question:

1. The problem must be related to a grand engineering challenge and/or students› everyday lives.
2. The problem must demonstrate more than one engineering theory covered in our curriculum.
3. The problem must require understanding and applying new concepts to solve.

For the third condition, we define new concepts as knowledge not covered in the prerequisite courses, which include: Thermodynamics, Fluid mechanics, Vibrations, Statistics, Basic computational skills in programming, finite element analysis and CAD, and basic measurement techniques for mechanical engineering. Table 1 shows the objectives for each week in responding to the central problem.

Table 1. The 1-2-3 Problem-solving lab structure. 1-Introduce, 2-Connect, and 3-Solve.

A Central Question - to inspire student curiosity

	Objectives
Week 1 - Introduce	• Learn new concepts and tools.
Week 2 - Connect	• Connect theories covered in the previous curriculum to the central question.
Week 3 - Solve	• Dissect a sub-component • Practice communication skills by replying to a supervisor's email, which describes an engineering problem and requests for a solution. • Solve problems by designing and conducting experiments.

Case Studies

We applied the 1-2-3 Problem-Solving Lab framework and created two three-week laboratory modules, one focusing on thermal fluid systems (the Battery Lab Module) and the other on mechanical systems (the Acoustics Lab Module). Each module was piloted as an elective class for around 20 students and then fully launched to 96 students in the following academic year. There were two 50-minute lectures and a 3-hour lab section each week. All students attended the same lectures each week but worked with their specific lab groups for their respective lab sections. Multiple lab sections were offered, and we maintained a maximum of 12 students per lab section to allow four teams of three students to perform the weekly experiment simultaneously. One graduate teaching assistant (TA) was assigned to lead two lab sections, and a faculty member oversaw all the TA training and teachings among multiple sections. Grader support was provided upon the course's full launch

Case 1: Thermal-fluid system (The Battery Lab)

Twenty-two students participated in the pilot of this lab, followed by ninety-six students in the full-scale offering in the second year. A modern challenge for engineers in both industrial and academic research was selected as the central question for this module – "How do we safely preheat Lithium-ion batteries in cold weather?" Table 2 summarizes the weekly objectives for the thermal system lab, also known as the battery lab.

Table 2. Summary of the Problem-Solving Thermal System Lab example – The Battery Lab.

The Central Question - How do we safely preheat Lithium-ion batteries in cold weather?

	Learning Objectives – By the end of the week, students will be able to
Week 1 New concepts and tools	• [New Concept] Define basic battery terminologies and concepts. Explain the real-world challenges in the field. • [New Tools] Perform battery discharging using high precision battery testing equipment (Arbin Battery Test System). • [New Concept] Explain how temperature affects battery performance and the need for preheating batteries in cold weather.
Week 2 Connect to theory	• [New/ Prior Knowledge] Apply conduction and convection strategies to preheat the battery. • [Link to Theory] Conduct experiments to measure temperature change and distribution to derive the batteries' thermal diffusivity and convective heat transfer coefficient.
Week 3 Sub-component and Problem-Solving	• [Sub-component] Explain the need for a feedback controller. • [Problem-Solving] ○ [Apply knowledge from Week 2] Find the thermal conductivity coefficient for a synthetic battery. ○ [Prior Knowledge + New Concept] Use numerical simulation to predict and evaluate the safety of battery preheating experiments proposed by the supervisor. ○ [Prior Knowledge + New Concept] Design a safe battery preheating experiment method under a given constraint.

Week 1: New concepts and tools

The first week focused on introducing new concepts and tools. Students learned battery terminology, chemistry, and charging and discharging processes. Students performed experiments by discharging 18650 Lithium-ion cells (2500mAh, 3.7V) using an Arbin Laboratory Battery Tester (LBT21084HC, Arbin, TX). The experimental goal was to study battery discharging performance in subzero temperatures. The discharging experiment was conducted inside four temperature chambers (BTU-433, ESPEC, MI), set to –19°C, –10°C, 4°C, and 22°C. Each team was assigned a different temperature to conduct the experiment, and the raw data was then shared among the class. The teams then analyzed the data and completed the discussion questions individually. We guided the students to examine the battery performance in terms of capacity and resistance to study the temperature effect on the ohmic resistance.

Week 2: Connect to theory

In the second week, the lab connected heat transfer theory to the practical challenge, preheating batteries in subzero environments. Using conduction and convection methods, students preheated the batteries in subzero environmental conditions, followed by measuring the preheated battery discharge performance. Students obtained heat transfer parameters from the experiments and compared them to literature and theoretical predictions. Then the studentsanalyzed the effectiveness of each preheating strategy by comparing the results to the previous week's subzero discharge data. Many students learned core thermodynamic and heat transfer theory in previous courses. However, the heat transfer class was not a prerequisite due to potential graduation conflicts. Therefore, the necessary theory was reviewed in lecture before each lab.

The conduction preheating setup is shown in Figure 1a. The battery was placed in a 3D-printed holder with surface thermocouples along the length and a metal heating block attached to one end. The setup was placed in the environmental chamber, and the test was conducted at subzero temperatures with the heating block set to 30°C. Students continuously monitored the temperature distribution along the battery from the five thermocouples along the longitudinal axis and manually turned off the heater to end the preheating process once the battery surface temperatures reached at least 2°C to start the battery discharging. By applying the general heat diffusion equation, students calculated the thermal diffusivity of the battery using the finite difference method. Assuming one-dimensional conduction heat flow with negligible convection and radiation, constant material properties, and no internal heat generation, thermal diffusivity (α can be obtained from the experimental data of temperature change against time and as a function of one-dimensional distance:

$$\alpha = \frac{\left(\frac{\partial T}{\partial t}\right)}{\left(\frac{\partial^2 T}{\partial x^2}\right)}$$

where T is temperature, t is time, and x is distance from the heater block.

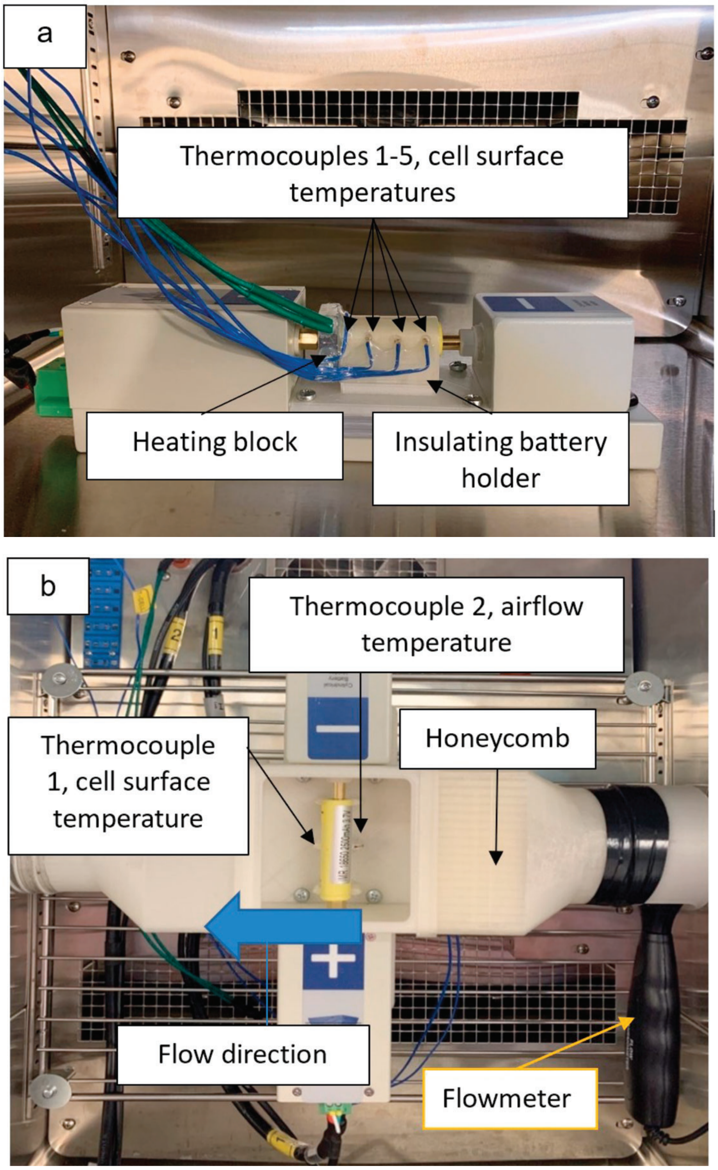


Figure 1. (a) Conduction experiment setup for preheating a single Li-ion battery. (b) Convection experiment chamber for preheating a single Li-ion battery with laminar airflow. Thermocouples and flowmeter locations are indicated in the figures.

The convection setup is shown in Figure 1b. This experiment was adopted from a heat transfer textbook (Incropera et al. 2006) example to allow students to visualize a conceptual calculation in practice. A convection chamber was fabricated with a honeycomb inlet to generate a fully developed laminar flow along the longitudinal side of a battery. Thermocouples measured the batteries' surface temperatures and a flowmeter provided the airflow velocity. The experiment was conducted in a subzero environmental chamber. Once the setup reached a steady state, warm air was used to preheat the battery. Students manually stopped the airflow when the cell surface temperature reached 10°C and then battery discharging began. The students then calculated the convection heat transfer coefficient from the experimental data and compared it to the theoretical value computed from the Zukauskas relation. Detailed calculations and assumptions can be found in Example 7.4 of the referenced textbook (Incropera et al. 2006).

In all of the experiments, the cell surface temperature was monitored and a safety precaution was programmed in the Arbin system to automatically shut down the test if a surface temperature exceeded 55°C.

Week 3: Sub-component and problem-solving

In week 3, the education outcome focused on the students' ability to solve semi-defined problems. The lab session starts with a standard heat conduction experiment, where students take temperature measurements along a synthetic battery with heat applied to one side. Subsequently, students were asked to create a numerical simulation replicating the physical experiments. Students were then expected to use their experimental data and simulation model to find answers for a few semi-defined problems outlined in an email as written by a supervisor to the teams. Students had to conduct experimentation using their computational models and respond to the supervisors' questions with data that supported their claims. In the email, three embedded questions were designed to focus on different problem-solving techniques, as summarized in Table 3.

Q.1 provided an opportunity to validate the students' understanding of the second week's material as they had to apply the same technique to a synthetic battery. For this setup, the experiment was operated at room temperature with the actual battery replaced by different metal rods to eliminate the danger of an overheated battery failure. Students were instructed to apply a specific

Table 3. Mapping of the problem-solving techniques students needed for each question.

Question	Problem-Solving Technique
Q.1 Determine the thermal diffusivities of a synthetic battery	• Recognize and adapt elements and methods from prior experiments. • Determine and implement the appropriate calculations as planned by the students
Q.2 Perform a safety evaluation for a proposed battery preheating method and support your conclusion via numerical simulation	• Define a goal or criteria. • Identify what important information needs to be generated. • Narrow down problems or identify related problems. • Evaluate any assumptions, simplifications made, and outcomes.
Q.3 Propose an alternative method to safely preheat the battery	• Design and conduct an appropriate experiment.

heater power for a given time duration and record the thermocouple readings at suggested time steps. Instructions for the data analysis phase were not provided to test if students could transfer their knowledge learned from the previous week. This question tests if students can use what they learned in the second-week lab to measure thermal diffusivity in a synthetic battery, building on their knowledge of measuring thermal conductivity in a real lithium-ion battery.

The second question was a poorly defined question designed to challenge the students' problem-solving and discernment skills, such as dissecting a problem, determining the goal, planning the solving process, and evaluating their solutions. The students were asked to evaluate the safety of the following proposed experiment and provide simulation data to validate their claim:

"Preheat the battery placed at a –10°C environment by connecting the heating element of the conduction module to a 12V 1A power source until the surface temperature at the far end of the battery, away from the heater, reaches the room temperature defined as 25°C."

While the above statement provided a condition to terminate the experiment, the criteria to answer the question about operational safety were left undefined. Students were required to identify safe operating conditions and support their decision. For safety reasons, students were asked to explore various experimental designs in this lab using numerical simulation methods. Table 4 presents a suggested workflow that we provided to the students to assist in guiding their thought process. Steps 2 and 3 of the workflow guided students to validate their simulation model with the known conditions of their physical experiments prior to modeling unknown situations. After validating their model, students could then proceed with steps 4 and 5 to conduct experiments with unknown outcomes.

Lastly, we designed question 3, "Propose an alternative method to safely preheat the battery", to encourage students to dissect a complex system. All the experiments proposed by the supervisor were intentionally designed to be unsafe. We anticipated that students would recognize the suggested experiment was nearly identical to the conduction experiment they conducted in week two,

Table 4. Week 3's suggested workflow for data collection, provided in the student lab manual.

1. **Design experiments** to find the thermal diffusivity of the given synthetic battery.
2. Create a **numerical simulation** in SolidWorks to mimic the conduction experiment for question 1.
3. **Compare your experimental** result in part 1 **with the simulation** result in part 2 to validate that the material properties are reasonable predictions.
4. **Simulate the proposed experiment** by your supervisor and comment on the safety of this experimental design.
5. **Simulate the second proposed experiment** (reduce power by 50%) by your supervisor and comment on the safety of this experimental design.
6. **Propose a better solution** and support your suggestion with simulations.

with the only difference being the removal of the PID controller. Students are required to analyze the role of the PID controller and understand how maintaining the heater at a specific temperature can transform the experimental design from being hazardous to safe. Encouraging unrestricted creativity in students, we were open to alternative experimental designs, provided that they can evaluate and prove their ideas with supporting data.

Case 2: Mechanical systems (The Acoustics Lab)

Twenty-three students participated in the pilot of this lab, followed by ninety-six students in the full-scale offering in the second year. All students completed our Computational Tools course as a prerequisite, focusing on finite element analysis, and had our Vibrations theory course as a corequisite. The central problem for this three-week module was derived from our common life experience: "Why does the same musical note sound different when played by different instruments?". This topic was suggested by our students, who noted that the working mechanism of musical instruments is connected to engineering principles but is seldom discussed in engineering curricula. The content in this lab can further extend to other engineering inventions, such as exhaust mufflers, amplifiers, noise-canceling headphones, and engineering techniques like controlling and measuring vibrations. The weekly objectives for the mechanical system lab, also known as the Acoustics lab, are summarized in Table 5.

Table 5. Summary of the Problem-Solving Mechanical System Lab example – The Acoustics Lab.

The Central Problem - Why does the same musical note sound different when played by different instruments?

	Learning Objectives – By the end of the week, students will be able to
Week 1 New concepts and tools	• [New Concept] Identify the characteristics of a sound wave. • [New Tools] Conduct an experiment to visualize vibration modes. • [New Tools] Measure vibration frequencies using an array microphone and accelerometer. • [New Concept] Identify the vibration frequencies for different vibration modes of a beam under free vibration via experimental designs.
Week 2 Connect to theory	• [Prior Knowledge] Conduct modal analysis in SolidWorks. • [Link to Theory] Predict the natural frequency of a free-free beam and alter the frequencies by varying the material thickness.
Week 3 Sub-component and Problem-Solving	• [Sub-component] Explain the effect of resonators. • [Problem-Solving] o [Prior Knowledge] Apply prior knowledge to extract the frequency content in audio data. o [Knowledge from Prior Labs] Prove their prediction by design and conduct experiments to measure sound waves. o [New Concept] Identify constructive and destructive interference locations at a given space.

Week 1: New concepts and tools

In the first week of lectures, students learned the fundamentals of Acoustics and sound waves. For the lab, the students began with vibration visualization and then applied different vibration measurements using an accelerometer and microphone on a random marimba bar. The marimba bars were taken from a 3.5 Octave Standard Padouk Marimba (YAM-YM40C, Yamaha, CA) and mounted on a custom-made bar holder. This holder was designed to be attached to the edge of any standard workbench, as shown in Figure 2a. Visualization was conducted by having sand on the marimba while playing the marimba, as shown in Figure 2a. Students obtained different sand patterns representing different vibration modes by changing where they hit the bar. Then teams performed vibration measurements using a single ICP® electret array microphone (Model 130F20, PBC, NY) and a single-axis accelerometer (352A21, PBC, NY). Data was acquired using a NI DAQ (cDAQ-9171, National Instrument, TX) paired with sound and vibration modules (NI-9234 C, National Instrument, TX). We instructed students to attach the accelerometer at various locations and hit the bar at either the center, side, or corner. Each accelerometer and hitting location combination emphasized a specific vibration mode. Students were then asked to identify the correlations by analyzing the collected data needed to identify the natural frequencies for the first five modes of vibrations, including 1st, 2nd, and 3rd transverse mode, 1st lateral mode, and 1st torsional mode, as illustrated in Figure 3.

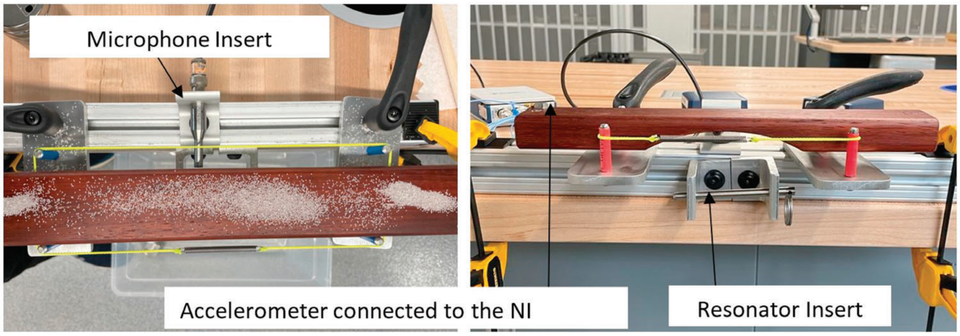


Figure 2. The top view and perspective view of the custom-made marimba bar holder. A microphone insert was designed to hold the microphone in place. Underneath the marimba is a resonator insert for students to study the effect of a resonator on musical instruments. The image on the left demonstrates a sand pattern students obtained to visualize vibrations.

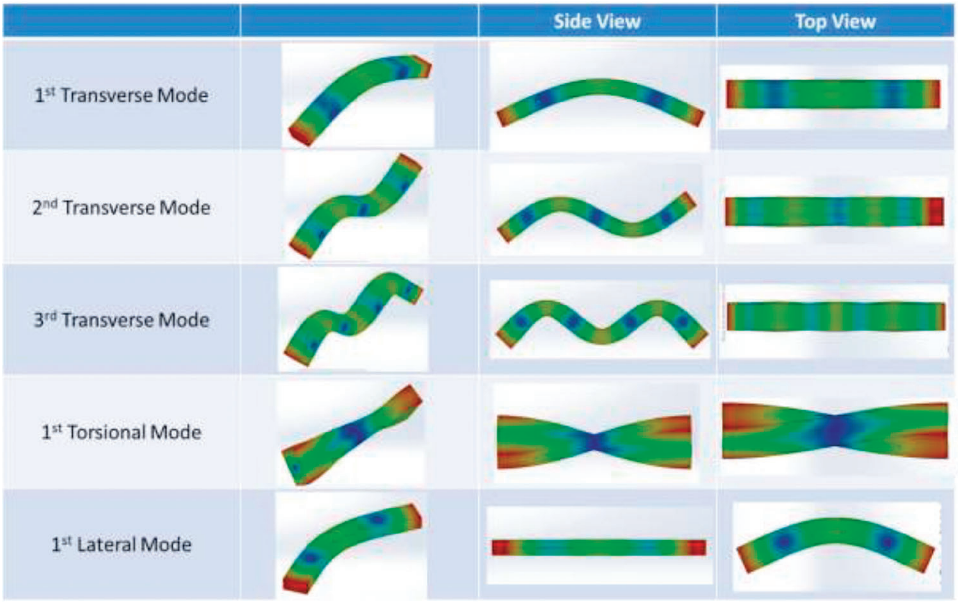


Figure 3. Illustration depicting the initial five modes of vibration of a rectangular bar, including 1st, 2nd, and 3rd transverse mode, 1st lateral mode, and 1st torsional mode.

Week 2: Connect to theory

In the second week, the course emphasized modal analysis and free-free beam vibration to study how marimba and xylophone bars are tuned. We challenged the students to alternate the natural frequencies of a wooden block, keeping the length and width as constant parameters while treating the thickness along the length as free variables in their simulations. The experimental goal was to simulate two wooden bars (one mimicking a marimba and the other a xylophone bar) with the same fundamental frequency but different overtone frequencies. The first overtone (2nd transverse mode) of a marimba is tuned to match the 4th harmonic of their fundamental frequency (1st transverse mode), and the second overtone is tuned to match the 10th harmonic. In contrast, the first overtone of a xylophone is tuned to match the 3rd harmonic of their fundamental frequency. This experiment aims to mimic the sanding process required in the production of each bar (or key) of the musical instruments. The distinction between a marimba bar and a xylophone bar is shown in Figure 4. By solving the Euler- Bernoulli Beam Theory with appropriate boundary conditions, students we able to predict the required thickness near the node or antinode locations to alter the natural frequencies of the overtones. This experiment was performed computationally using modal analysis in SolidWorks to allow students to continuously iterate on their predictions.

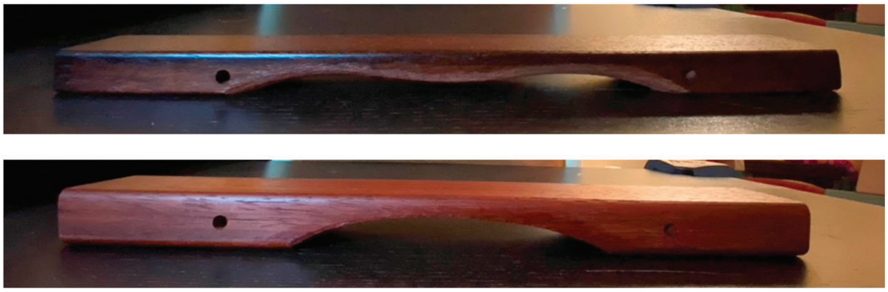


Figure 4. The contrast in cross-sectional sanding between a marimba bar (top) and a xylophone bar (bottom).

Week 3: Sub-component and problem-solving

In week three, we focused on analyzing a sub-component and problem-solving. The lab began by concentrating on a sub-component of a marimba - the resonators. Students performed microphone measurements on a marimba bar and compared the results with and without the corresponding resonator tubes to understand the effect of the resonator on frequency responses. In the second part, students practiced problem-solving techniques with a well-defined question. We gave each team an email written by a supervisor with an attached sound recording of a signal tone. The supervisor asked the team to identify which marimba bar produced the tone and whether a resonator was attached. Teams then needed to perform experiments to replicate the recording and collect data to support their findings. Lastly, the laboratory module ends with an essential concept in the study of sound waves: interference. Students studied sound interference by calculating the constructive and destructive interference locations inside a room when two speakers played the recorded tone synchronously.

The educational goal in this section was for students to apply what they learned from the previous two weeks to design and conduct an experiment to solve their problem. Here the problem was to identify the source of the recording, replicate it, and confirm the recording was identical to the provided one. This activity challenged students' ability to solve a problem systemically within a limited time and their ability to identify the information from the recording needed to narrow down the 84 possible options. Without explicitly mentioning it in the protocol, we expected students to apply their Fourier analysis knowledge, learned from the prerequisite courses, to solve this problem. To confirm their prediction on whether a resonator was attached and to replicate the recording, we challenged their ability to apply the experimental method learned in the first week and the resonator section to perform vibration measurement, evaluate their results, and validate their assumptions.

Course Deliverables

The set of deliverables for the three-week module included submitting three weekly lab submissions, an individual homework assignment, and a group report. These lab submissions consisted of experiment results and discussion sections. The results section allowed students to document their collected data. The discussion questions were intentionally crafted to prompt students to demonstrate a thorough comprehension of the purpose behind each experiment. For instance, in Acoustic Lab 1, students were prompted to explain the transformation of the sand pattern on a marimba bar after gently tapping its center with a mallet, resulting in two tilted lines, instead of the vertically perpendicular lines, to the longitudinal side of the bar. Furthermore, students were tasked with comparing data from the sand method, microphone, and accelerometer measurements to identify the natural frequencies of the five vibration modes. In Battery Lab 1, the students were asked to calculate the ohmic resistance of batteries using voltage drop data to study why the discharge performance of batteries varies with different environmental temperatures.

All group reports for the two presented problem-solving labs followed a standardized format. Students are required to respond to an email authored by their supervisor, and these emails encompass four key elements that need students to perform analysis and evaluations. The four criteria are:

1. Define criteria to address the supervisor›s inquiry.
2. Identify the connections between labs or make use of prior knowledge
3. Generate data or evidence to justify their claims
4. Make a selection among multiple options

Besides grading on technical content, we also assess students' technical writing skills for a wide range of audiences in this report for ABET purposes.

Student feedback and performance

A survey was performed to collect student feedback after the completion of the modules. A eleven-point Likert scale (Likert, 1932) was used to assess the students' interest level during the three-week modules. A five-point Likert scale was used to evaluate the difficulty level of the materials, learning environment, real-world application of the topic, and application of thinking skills. Lastly, in the open-ended questions, students were asked to share how they applied analytical skills in the lab. In the pilot courses, 18 out of 22 students participated in the Batteries Lab survey, and 23 out of 23 students participated in the Acoustics Lab survey. In the full-scale course, launched after the pilot phase, 85 out of 96 students participated in the Batteries Lab survey, and 89 out of 96 students participated in the Acoustics Lab survey. In addition to the student surveys, we analyzed 32 student team reports from each case study, totaling 64 reports in the full-scale course. This evaluation aimed to assess student performance in the four key elements listed in the previous section, which are focused on conducting analyses and evaluations embedded within the email reports.

RESULTS

Interest Level, Difficulty Level, and Real-World Impact

The students were surveyed to assess their overall interest in the lab activities, rated on an eleven-point scale, ranging from 0 (Not at all interesting) to 10 (Very interesting). We observed that the Acoustics Lab was deemed more interesting by the students compared to the Batteries Lab. In the pilot study, the Acoustics Lab received mostly ratings in the somewhat interesting range (7-8) with a mean, standard deviation, and median of 8.04 ±1.20 and 7.00, respectively. The ratings were slightly lower in the full-scale study, yielding a mean and median of 6.58 ±1.84 and 7.00. The Batteries labs received ratings mostly between neutral and somewhat interesting (4-8). In the pilot study, the mean and median were 5.72 ±2.74 and 6.00, while for the full-scale offering, they were 5.41 ±2.26 and 6.00. The detailed student ratings are summarized in Figure 5.

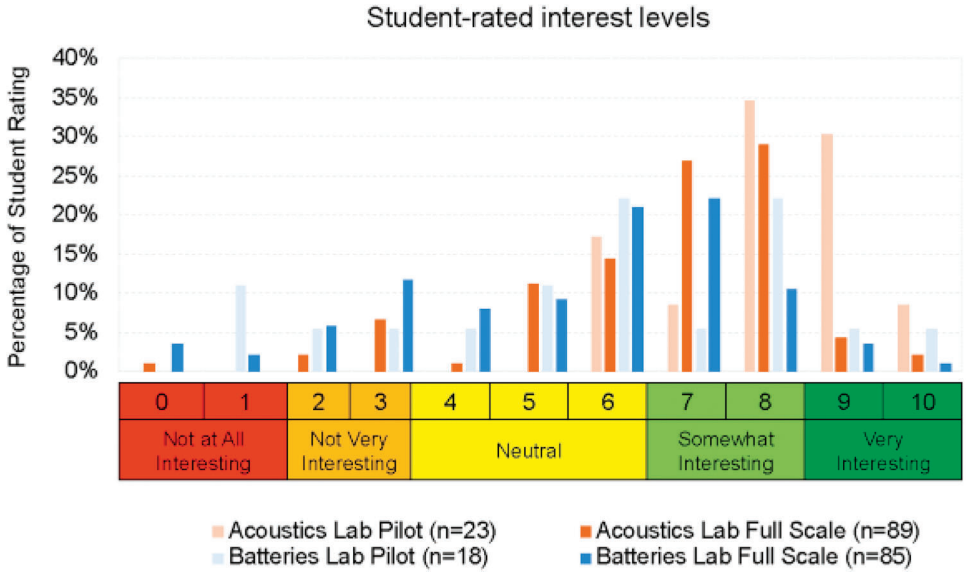


Figure 5. Student responses on the overall interest level of the Acoustics and Battery Labs.

The difficulty level of the labs was rated on a five-point scale ranging from very difficult (1) to too easy (5). According to student ratings, the Acoustics Lab was deemed to have an appropriate difficulty level for both the pilot and full-scale offerings, with a mean and median of 2.87±0.45 and 3.0 for the pilot, and 2.71±0.50 and 3.00 for the full-scale offering. In contrast, the Batteries Lab received a higher level of difficulty rating, with a mean and median of 1.94±0.85 and 2.00 for the pilot, and 2.26 ±0.67 and 2.00 for the full-scale offering. The detailed student ratings are summarized in Figure 6.

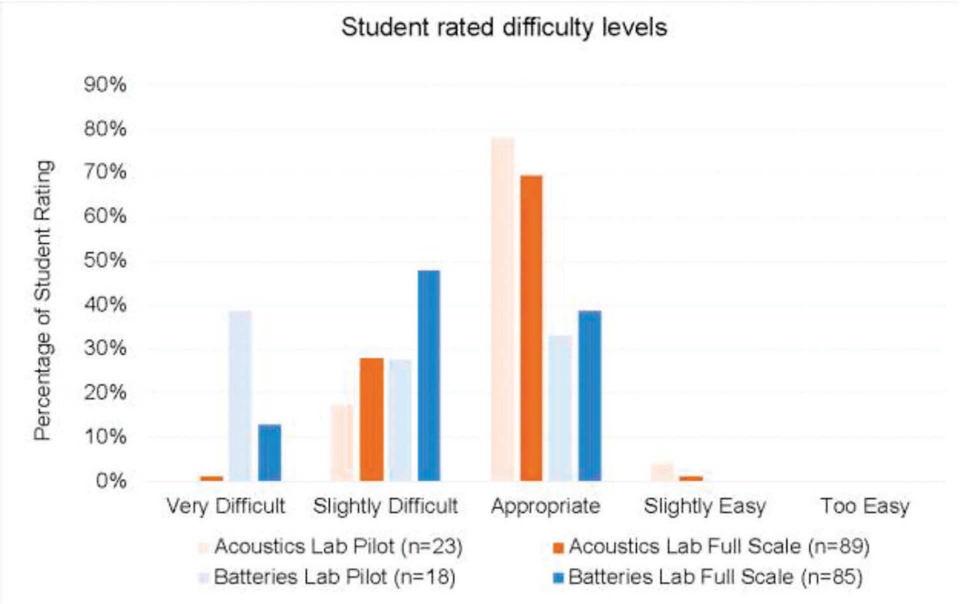


Figure 6. Student responses on the overall difficulty level of the Acoustics and Battery Labs.

We assessed the students' perspectives on how they felt the course materials connected to the real world on a five-point scale. In the pilot of the Acoustics Lab, 100% of the students agreed or strongly agreed the lab demonstrated a real-world application to the topics of vibrations and acoustics. In the full-scale offering with 89 students, the majority (87.7 %) of the students agreed or strongly agreed the lab demonstrated a real-world application to the topics. In the pilot of the Batteries lab, 67% of the students agreed or strongly agreed the lab presents a real-world technology barrier for lithium-ion batteries, and the remaining 33% of the students rated neutral. In the Battery lab's full-scale survey, we updated the question to ask whether the lab demonstrated real-world application to the topics of heat transfer. This updated question was more closely aligned with the learning objectives of the lab design and comparable to the Acoustics lab question. In the full-scale offering with 85 students, the majority (76%) of the students agreed or strongly agreed that the lab demonstrated a real-world application to the topics. The collected data are listed in Table 6.

Encourage Thinking

This design framework aims to prompt students to use their critical thinking abilities to solve engineering challenges. We specifically target two essential cognitive skills: Analysis and Evaluation. In

Table 6. Student responses on the relevance of materials to real-world application. The top two student choices are highlighted.

	Statements		**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
Acoustics Lab Pilot (n=23)	The labs demonstrated real-world applications to the topics of vibrations and acoustics.	Freq	0	0	0	16	7
		%	–	–	–	69.6%	30.4%
Acoustics Lab Full-Scale (n=89)	The labs demonstrated real-world applications to the topics of vibrations and acoustics.	Freq	1	0	10	59	19
		%	1.1%	–	11.2%	66.3%	21.4%
Batteries Lab Pilot (n=18)	The labs demonstrated real-world applications to the technology barriers of lithium-ion battery.	Freq	–	–	6	8	4
		%	–	–	33.3%	44.5%	22.2%
Battery Lab Full-Scale (n=85)	The labs demonstrated real-world applications to the topics of heat transfers.	Freq	1	4	15	51	14
		%	1.0%	5.0%	18.0%	60.0%	16.0%

our initial assessment, we gauged the students' awareness of their critical thinking using Likert scale questions and open-ended reflections in both pilot classes. The detailed data is summarized in Table 7.

Within the Acoustics Lab, 91% of students either agreed or strongly agreed that the lab activities prompted them to contemplate the cause-and-effect relationship. Additionally, out of 23 students, 22 were able to describe a relevant lab activity where they applied their analytical skills, including those who provided a neutral response to the question above. The descripted moments included identifying the vibration frequencies for different vibration modes (Week 1), modal analysis in SolidWorks (Week 2), analyzing the sound recording (Week 3), and identifying interference locations in a room (Week 3). When asked to articulate a moment of applying analytical skills, most students referred to an activity from Week 3.

Table 7. Student assessment of the pilot course materials encourages their thinking.

Acoustics Lab Pilot (n=23)

Statements		**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
The lab activities encourage me to think about the cause-and-effect relationship.	Freq	–	–	2	17	4
	%	–	–	8.70%	73.91%	19.39%

Battery Lab Pilot (n=18)

Statements		**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
The lab activities encourage me to think and find a solution by myself.	Freq	–	2	5	9	2
	%	–	11.11%	27.78%	50%	11.11%

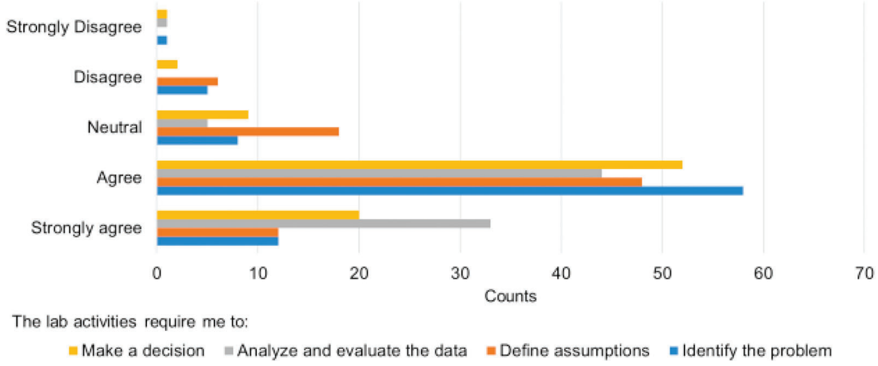
For the Batteries Lab, 61% of the students agreed or strongly agreed that the lab activities encourage them to think and find a solution themselves. Additionally, 17 out of 18 students, including those who rated neutral or disagreed with the above question, could describe a relevant moment they applied their analytical skills in the lab. The described moments were understanding and explaining how temperature affected battery performance from experimental data (Week 1), troubleshooting experiments (Week 1), extracting heat transfer coefficients from experimental results (Weeks 2 and 3), and constructing numerical simulation models to evaluate the safety of experiment designs (Week 3). The most frequently referenced action was data analysis, particularly extracting the thermal diffusivities from experimental data in Weeks 2 and 3.

During the full-scale offering, we selected the Batteries Lab to study whether the course materials required students to apply different problem-solving techniques. The four selected techniques were identifying problems, defining assumptions, analyzing and evaluating data, and making a decision. This analysis showed 83% of the students agreed or strongly agreed the lab required them to identify the problem, 71% agreed or strongly agreed the lab required them to define assumptions, 93% agreed or strongly agreed the lab required them to analyze and evaluate their data, and 86% agreed or strongly agreed the lab required them to make a decision. Overall, 84% of the students agreed or strongly agreed the lab activities encourage them to think about the cause-and-effect relationship. The detailed data are summarized in Table 8.

Table 8. Student assessment of the Batteries course materials on encouraging their thinking and the application of four different problem-solving techniques: identify problems, define assumptions, analyze and evaluate data, and make a decision.

Batteries Lab Full-scale (n=84)

Statements		**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
The lab activities encourage me to think about the cause-and-effect relationship.	Freq	1	1	11	45	26
	%	1.19%	1.19%	13.10%	53.57%	30.95%



In addition to indirect measures obtained from student surveys, we assessed student lab reports in the full-scale offering to evaluate the four factors linked to analyzing and evaluating problems. These factors encompassed defining criteria, recognizing correlations, making evidence-based decisions, and choosing alternatives. The imperative to apply analytical skills was integrated into every weekly lab activity, with multiple questions in the lab submission necessitating this skill set. Students, in their open-ended survey feedback, also recognized and noted this integration. To standardize the assessment, we chose one question from the last laboratory session to evaluate student performance in analyzing and evaluating problems. The findings from this evaluation are outlined in Table 9.

In the Battery Lab, the supervisor's email asked students to calculate the thermal diffusivity of a synthetic battery and use computational methods to study the safety of several proposed experiments. Students were tasked with defining criteria to address the supervisor's inquiry and quantify the safety definition in this case. Our results indicated that all student teams could recognize that safety was related to cell surface temperature. Secondly, we expected students to recognize the similarities between the lab activities and to be able to apply similar data analysis strategies to study thermal diffusivity. It was found that 90.63% of the teams were able to use their knowledge of extracting thermal diffusivity from an actual Li-ion battery from the conduction lab in week two to calculate the thermal conductivity of a synthetic battery. The remaining teams could apply the method, but their calculations contained errors. Additionally, we studied students' ability to generate data and evidence to justify their claims without step-by-step instructions or a prescribed list of necessary data. We observed that 68.75% of the teams were able to generate appropriate and sufficient data, while 25.00% missed some essential information. Lastly, the supervisor's proposed experiments had four thermocouples evenly mounted along the longitudinal axis of the battery, and a heater was connected at one end. We analyzed if students could identify which thermocouples they should monitor to evaluate if the proposed preheating operations were safe. Their given experimental goal was to preheat the battery until the temperature at the far end of the battery from the heater reached room temperature. While 68.75% of the teams made correct selections among the four options by monitoring both thermocouples closest to the heater and the far end of the battery, 25.00% made an error even though their explanation contained reasonings for their decision.

We performed a similar assessment with the Acoustics lab reports. The selected question is whether students can identify the pitch of a single-note marimba sound recording and determine if a resonator was used. They are required to prove their prediction and make a correct selection from the 96 options. We found 96.88% of the teams could identify that the frequency information from the provided sound recording needed to be extracted to answer

Table 9. Grading Rubrics and Assessment Results for the Four Key Factors in Analyzing and Evaluating Problems: Criteria Definition, Correlation Recognition, Evidence-Based Decision-Making, and Alternative Selection. (n=32 teams for each case study)

Battery lab: Assessment Tools: Student Lab Report (Email) and Lab 3 Submission

Assessment Question: Calculate the thermal diffusivity of a synthetic battery and use computational methods to study the safety of several proposed experiments.

	Excellent	Counts	Acceptable	Counts	Unmet	Counts
Define criteria to address the supervisor's inquiry.	Recognize that battery safety is related to cell surface temperature.	32			Unable to relate battery safety to cell surface temperature.	
Recognize the interrelationships between different laboratory activities previous knowledge.	Apply knowledge from the conduction lab to calculate thermal diffusivity. The calculation is correct.	29	Apply knowledge from the conduction lab to calculate thermal diffusivity. The calculation contains errors.	3	Unable to perform the calculations.	
Generate data or evidence to justify their claims	Generate appropriate and sufficient data to answer the questions.	22	Generate appropriate data to answer the question, but some essential data needs to be included, or human error occured.	8	Generate unrelated data or does not provide any data.	1
Make a selection among more than one options	Identify the safe operation temperature correctly and monitor the appropriate thermocouples from various locations.	22	Choose by applying some logical reasoning. Errors occur due to insufficient data, misinterpretation, or human error.	8	Choose randomly or contain major issues in reasoning.	1

Acoustic Lab: Assessment Tools: Student Lab Report (Email) and Lab 3 Submission

Assessment Question: Identify the pitch of a single-note marimba sound recording and determine if a resonator is used. Students are required to prove their prediction and make a correct selection from the 96 options.

	Excellent	Counts	Acceptable	Counts	Unmet	Counts
Define criteria to address the supervisor's inquiry.	Recognize the need to perform frequency analysis.	31			Unable to recognize the need to perform frequency analysis.	1
Recognize the interrelationships between different laboratory activities previous knowledge.	Apply knowledge from the sound measurement lab or prerequisite courses to perform FFT analysis.	31			Unable to find a method to analysis the recording.	1
Generate data or evidence to justify their claims	Generate appropriate and sufficient data to answer the question.	15	Generate appropriate data to answer the question, but some essential data is missing, or human error occurred.	15	Generate unrelated data or does not provide any data.	2
Make a selection among more than one options	Select the correct option and use the data to justify their conclusion.	11	Select the incorrect option while still applying some logical reasoning. Errors occur due to insufficient data, misinterpretation, or human error.	20	Choose randomly, whether right or wrong.	1

the pitch question. Those students could also apply their learning from previous labs or prerequisite courses to perform Fast Fourier Transform (FFT) analysis. To produce a data-driven conclusion to confirm the pitch of the recording and whether a resonator was used, 46.8% of the teams were able to generate appropriate and sufficient data without written instructions explicitly listed in the lab manual. Another 46.8% of the students could generate some proper data, but some essential information needed to be included, or human error occurred. 6.25% of the teams were not able to generate related data. Lastly, 34.38% of the students were able to select the correct marimba bar and resonator combination from the 96 options using their collected information, and 62.50% made a selection with some logical thinking, but the choice was incorrect.

Combining observations from both studies, we found that over 93% of the teams applied analytical skills, including defining criteria, recognizing correlations, making evidence-based decisions, and selecting alternatives to complete their lab assignments. While some students made errors in decision-making or failed to generate all the essential data, they still demonstrated proficiency in data analysis and critical thinking skills to conduct their lab work. This observation aligns well with the subjective assessment results collected from individual students through survey data presented in the earlier section, indicating that 84.52% of students agreed that the lab activities encouraged them to consider cause-and-effect relationships. Therefore, we are confident that students effectively applied analytical skills in these labs. The majority of them assessed the questions they aimed to address, identified commonalities across labs, determined the necessary facts and data for drawing conclusions, and made decisions based on the available information.

Connectivity to the ME Curriculum

Our problem-solving lab framework was designed to demonstrate more than one engineering topic in the curriculum. The Acoustics Lab was designed to focus on topics in Vibrations and Computational Tools, while the Batteries Lab focused on Heat Transfer and Computational Tools. We asked students to vote on which class(es) within the ME curriculum had prepared them for the lab, and the result is summarized in Table 10. Unsurprisingly, the selected topics were the top-rated relevant courses. For the Acoustics Lab, the other courses students recognized included General Math and Physics from their first two years, a Circuit and Measurement course from their third year, and a Modeling of Dynamic Systems course from their fourth year. For the Batteries Lab, other courses students recognized included General Chemistry from their first year, a Thermodynamics course from their second year, a Circuit and Measurement course from their third year, and a Mechatronics course from their fourth year.

Table 10. Students vote on the relevance of the lab activities to other courses in the curriculum.

Acoustics Lab

Which of the following class(es) had prepared you for the Acoustics Lab? (Allow multiple selections)	Number of Students Pilot (n1=23) %	 Full-scale (n2=88) %
Matrices (General Math)	4.35%	4.55%
Ordinary and Partial Differential Equations (General Math)	8.70%	13.64%
Computational Tools	65.22%	38.64%
Circuit and Measurement	26.09%	23.86%
Vibrations	86.96%	87.50%
Modeling of Dynamic Systems	21.74%	11.36%
Wave Motion and Quantum Physics (General Physics)	8.70%	11.36%

Battery Lab

Which of the following ME class(es) had prepared you for the Battery Lab? (Allow multiple selections)	Number of Students Pilot (n1=18) %	 Full-scale (n2=85) %
Thermodynamics	22.22%	36.47%
Fluid Mechanics	11.11%	24.71%
Computational Tools	50.00%	64.71%
Heat Transfer	72.22%	78.82%
Circuit and Measurement	5.56%	4.71%
Mechatronics	5.56%	0.00%

DISCUSSION AND FUTURE WORK

This paper summarized the design framework we used to develop a problem-solving lab that applied real-world problems to empower students' cognitive skills in Analysis and Evaluation. Two case studies were presented, one for thermal fluid systems (the Batteries Lab) and another for mechanical systems (the Acoustics Lab). The collected student feedback demonstrated that most students (over 80%) agreed the three-week activities encouraged them to think, and their analytical skills were applied in multiple stages throughout the lab modules. In addition, students observed more than one engineering principle they learned in the ME curriculum was applied during the lab to a real-world problem.

Comparing the student-rated overall interest level of the two case studies, students generally found the Acoustics Lab more interesting than the Batteries Lab. We observed their interest levels might be affected by whether students see the connection between their work and the real-world problem and the difficulty level of the materials. In the pilot study, three students who rated the overall interest level as not very interesting to not at all interesting (<= 3) expressed neutral feelings in seeing the connection of the lab activities to real-world problems, and they all rated the course material as very difficult. On the other hand, the twenty-six students who rated the overall interest level as somewhat interesting to very interesting (>= 7) agreed or strongly agreed the labs demonstrated real-world application to the topics. They had mixed inputs on the difficulty level of the materials, from very difficult to slightly easy.

In the full-scale offering, we further studied the effects of real-world connection and difficulty level on student interest levels. Consistently, in both the Batteries and Acoustics labs, we observed the highest interest level rating from students who strongly agreed the lab demonstrated real-world application. The decrease in interest level followed the reduction in agreement that the lab demonstrated a real-world application. The difficulty level is another factor that seemed to influence the student interest, and the impact is significant when students felt the lab was very difficult but less significant when the lab's difficulty level was rated between slightly easy to slightly difficult. The detailed data are summarized in Table 11.

Table 11. Comparison of students' rated interest levels to the real-world connection and lab difficulty level. The groups with the highest interest level rating from students are bold.

		Acoustics Lab full-scale offering					
		Students-rated Interest Levels within each group.					
		Mean +/– Standard Deviation (s.d.)	**n**			**Mean +/– s.d.**	**n**
The labs demonstrated real-world applications.	**Strongly Agreed**	**7.68+/– 1.26**	**19**	The difficulty level the lab.	Too Easy	NA	0
	Agreed	6.64+/– 1.63	59		**Slightly Easy**	**7.00+/– 0.00**	1
	Neutral	4.80 +/– 1.25	10		Appropriate	6.68 +/– 1.79	62
	Disagreed	NA	0		Slightly Difficult	6.60 +/– 1.55	25
	Strongly Disagreed	0	1		Very Difficult	0	1
The overall interest rating is 6.58 +/– 1.84 (n=89)							

		Batteries Lab full-scale offering					
		Students-rated Interest Levels within each group.					
		Mean +/– (s.d.)	**n**			**Mean +/– s.d.**	**n**
The labs demonstrated real-world applications.	**Strongly Agreed**	**7.71+/– 1.62**	**14**	The difficulty level the lab.	Too Easy	NA	0
	Agreed	6.02+/– 1.75	51		Slightly Easy	NA	0
	Neutral	3.27 +/– 1.98	15		**Appropriate**	**6.39 +/– 1.97**	**33**
	Disagreed	2.50 +/– 1.12	4		Slightly Difficult	5.12 +/– 2.06	41
	Strongly Disagreed	0	1		Very Difficult	3.55 +/– 2.77	11
The overall interest rating is 5.41 +/– 2.26 (n=85)							

In the Batteries Lab pilot, over 83% of the students felt they had insufficient time to complete the lab work, while none of the students stated this for the Acoustics lab pilot. Based on this feedback, we reduced the content of the Batteries Lab and continued data collection to further study the impact of insufficient time in the full-scale offering. Similar to the pilot study, we observed the lowest mean interest rating from students who reported inadequate time in the full-scale offering of the Batteries Lab. The mean interest rating was 6.11 ± 2.04, 5.61 ± 1.99, and 4.14 ± 2.44 in the student groups who responded “sufficient,” “maybe,” and “insufficient” to the question: Did you have sufficient time to complete the work? Students who felt they had insufficient time may have felt rushed or overwhelmed, which could have impacted their ability to fully engage with the lab materials and maintain their interest in the subject matter. However, a more in-depth study will be needed to conclude.

Interest is a powerful tool to motivate and engage learners (Harackiewicz, Smith, and Priniski 2016). When students are interested in a subject, they are more likely to actively participate in learning activities and persist when faced with challenges. Alternatively, a lack of interest discourages students from learning. Therefore, it is essential that educators create a learning environment that fosters student interest. One way to do this is by continually demonstrating the real-world application of engineering principles in their problem-solving labs. Seeing the impact of their knowledge encourages students to develop a deeper understanding of the material. Another critical aspect in designing a problem-solving lab is well-balanced problems that are challenging yet achievable within an allotted period. This can reduce students feeling overwhelmed by their tasks, therefore, maintaining student interest. Lastly, the laboratory work needs to integrate information from various stages of the curriculum. By pulling together and connecting previous course material, students can better understand the multi-disciplinary and diverse world of engineering. In summary, a well-designed lab that balances student interest, presents real-world impact, provides appropriate time to perform tasks, and connects prior knowledge to lab assignments can motivate students to critically think through and solve challenging problems.

Based on our survey data, most of the students reported our design framework required them to apply problem-solving skills to identify a problem, define assumptions, analyze and evaluate their data, make a decision, and consider the cause-and-effect relationships. This perception was found to be independent of their interest level or perceived complexity of the problems. Our design framework provides a foundation for educators to redesign traditional labs into problem-based labs that lead students in connecting their learning to practical application. In the future, we plan to perform qualitative assessments of students' work to validate the impact of our design strategies on encouraging problem-solving. Additionally, we will continue to optimize our design framework and share it with the community so educators can better shape their courses, minimize design failure, and maximize student success.

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