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Building Better Engineers: Teaching Chemical Engineers to Troubleshoot in the Laboratory

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Abstract

The Chemical Engineering Laboratory is a crucial training ground for students to acquire fundamental professional skills. Among these skills, troubleshooting is exceptionally valuable and significant, yet it is often underemphasized in the engineering curriculum. This study examines the efficacy of structured troubleshooting training modules in enhancing students' troubleshooting skills. Modules were integrated into laboratory lectures to introduce troubleshooting concepts, followed by a hands-on exercise to evaluate proficiency. Teaching assistants assessed student performance and recorded observations on troubleshooting approaches and strategies. Results suggest that structured training modules improve troubleshooting skills. Our findings highlight the importance of dedicated pedagogy in enhancing student troubleshooting performance.

Introduction

Unit operations is a staple course included in Chemical Engineering undergraduate programs. The course includes a breadth of learning objectives that provide the student with experience using engineering equipment, collecting and analyzing engineering data, comparing experimental results to theory, designing experimental procedures or strategies, and identifying experimental problems [1]. Unit Operations, which we will refer to as Chemical Engineering Laboratory courses, also provide opportunities for students to gain professional skills in teamwork, communication, problem-solving and critical thinking.

The use of benchtop or pilot scale equipment provides real-world context, and, just as when a piece of equipment fails or does not operate as expected in the real-world, students might be expected to troubleshoot the problem to regain expected operation. Lab instructors consider this troubleshooting to be an integral professional skill vital to student success. Mistakes in the laboratory are inevitable and students who participate in troubleshooting can benefit by “learning from failure”. Moreover, the act of troubleshooting requires that students develop a broader set of skills that might include gathering sensory information, forming predictive models, using appropriate instrumentation, and analyzing data [1].

Engineering students may already possess troubleshooting skills, such as those gained from repairing household items. However, this proficiency does not always transfer to the laboratory environment, and troubleshooting laboratory equipment in a Chemical Engineering Laboratory can be challenging [2] and frustrating [5] for students. This difference in skill proficiency can be attributed to the need for different types of knowledge and the application of that knowledge while acquiring new skills for solving engineering problems [5]. For instance, when dealing with a circuit, students may identify a fault in the system, but their awareness and understanding of these errors are still developing, limiting their ability to diagnose and address the issue.

Just as we train students in technical writing, statistics, or presentations, proficiency in troubleshooting requires structured training. However, there are many challenges to effective troubleshooting instruction; teaching the principles and strategies of troubleshooting is often not an explicit goal in many courses, there is generally a lack of resources on how to structure this deliberate training, and there are few methods for easily assessing troubleshooting abilities. As a result, much troubleshooting instruction focuses more on the use of an appropriate tool, e.g., a debugging tool to address a problem [3,4].

In this study, **our research goal was to assess the impact that intentional troubleshooting instruction had on the troubleshooting performance of a group of senior Chemical Engineering student**s. To achieve this goal, we integrated two troubleshooting instruction modules into our laboratory lecture series. To assess their troubleshooting skills, we further required that all students complete a hands-on troubleshooting exercise at the end of term.

Background

General frameworks for troubleshooting are transferrable across different domains and levels of domain expertise. These frameworks often comprise of a cyclic sequence of distinct steps, such as seen in Figure 1 [8]. Troubleshooting frameworks provide an excellent starting point for instructing students because they reveal a systematic, relatively intuitive approach.

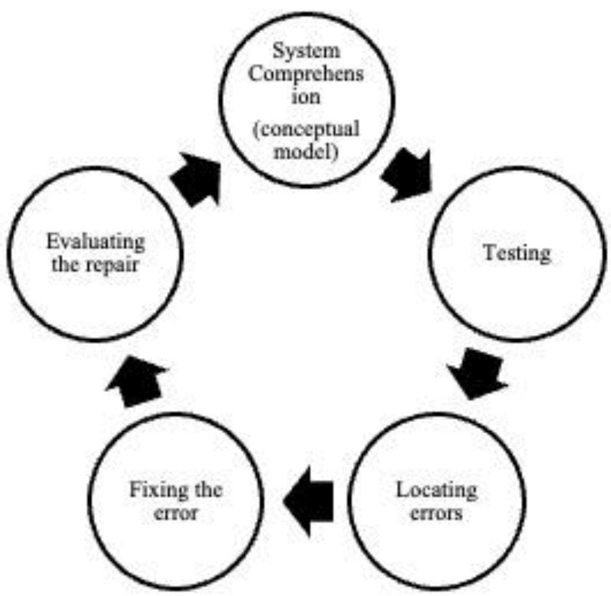

Figure 1. General troubleshooting recreated from [8].

Engineering students are likely to be familiar with the general troubleshooting process as it is quite intuitive. However, without instruction to highlight how this framework might be deployed, students may jump haphazardly from step to step without taking time to consider the systematic nature of troubleshooting [2].

Within this framework, students might employ different troubleshooting strategies. The below list highlights some of the common troubleshooting strategies that transcend domains [4,5] along with examples relevant to the operation of a chemical engineering heat exchanger.

- **Trial and Error:** A common strategy whereby different solutions are tried until the problem is resolved. (e.g., various water and steam valves are opened and closed until flow is established)
- **Exhaustive:** A thorough examination and testing of all possible causes is completed with the goal being to pinpoint the issue. (e.g., pressure or temperature data is gathered for each steam valve to validate operation)
- **Topographic:** A common approach whereby the troubleshooting aims to understand the system's structure and components through tracing the system to identify the source of the problem (e.g., water pipes are traced from inlet to outlet to understand function and identify open/closed valves)
- **Split-Half:** The system is divided into parts and the problem is isolated by testing each section separately. Also referred to as chunking. (e.g., steam and water sections are divided and investigated separately)
- **Discrepancy Detection:** This strategy emphasizes the identification of discrepancies or deviations from expected system behavior to locate faults. (e.g., unexpected temperature data used to identify a fault and the location of the fault)

Van De Bogart et al. [6] and Adams et al. [7] provide two examples of deliberate troubleshooting instruction and how to assess troubleshooting skill in the engineering classroom. Van De Bogart et al. [6] devised a troubleshooting exercise wherein students were tasked with identifying and repairing two faults in an electric circuit. Working in pairs, students were encouraged to "think aloud" and verbalize their thought processes, offering insight into the knowledge and strategies used for troubleshooting and gauging their understanding of the circuit. Inquiry-guided laboratory manuals have also been used to foster students' independence in the laboratory [7]. The objective of this approach was to normalize mistakes and promote an iterative troubleshooting approach.

Methods

This study used qualitative observations to assess the impact of troubleshooting-specific learning modules on the troubleshooting proficiency of chemical engineering students when faced with a chemical engineering challenge. Participants (*n=34*) were enrolled in a chemical engineering laboratory course at the University of Virginia. They participated in two dedicated lectures on troubleshooting before engaging in a laboratory-based troubleshooting assessment. The exercise was adapted from prior research [2] and will be described below.

Course Setting and Participants

The 4th-year chemical engineering lab course focuses on fundamental concepts including experimentation, teamwork, technical communication, and safety. Students spend four hours in lab each week investigating complex experimental problems. Each experimental problem requires four-weeks of investigation and students complete three experiments over the course of the term. Additionally, a 50-minute lecture is conducted weekly to provide training in communication, teamwork, safety, and experimental design.

Students undergo assessment through various technical writing formats (e.g., technical memos, full reports, emails, presentations) and a 60-minute desk-based final exam evaluates their conceptual grasp of engineering principles, laboratory procedures, and results interpretation. As part of this study, an in-lab troubleshooting exercise was integrated into the assessment. Participation in this exercise was mandatory for all enrolled students, with grading based on a Pass/Fail criterion.

Approval to collect data for this study was granted by the UVA IRB, protocol number 6204. Students were asked to complete a consent form indicating their willingness to share their data for use in this study. There was no incentive to consent. Consent for data evaluation was obtained from 34 out of 42 students.

Troubleshooting Learning Modules

Two troubleshooting learning modules were developed to teach students the basic principles of troubleshooting and to provide them with experience solving problems. The modules comprised a hands-on component whereby students could learn through practice, and this was coupled with a debrief and discussion about the process and techniques employed to solve the problem.

Specifically, each lecture began with students engaging in a learning module. The module was introduced with minimal instruction to enable observation of the students' initial troubleshooting tendencies. Following completion of the exercise, the instructor facilitated a discussion on students' approaches, the strategies used, and challenges they faced. These discussions revealed several common strategies, which were subsequently supported by the instructor with additional lecture content describing the troubleshooting process (Figure 1), commonly employed troubleshooting strategies, and the significance of domain knowledge.

Module 1. Valley of the Kings: The first troubleshooting module was adapted from Michaeli and Romeike's [4] use of escape room tasks for teaching code debugging, reflecting the growing interest in live escape rooms as training tools.

In this module, students were provided with the coded map in Figure 2, featuring a highlighted route, directional instructions in a legend, and directional arrows corresponding to the route. Six

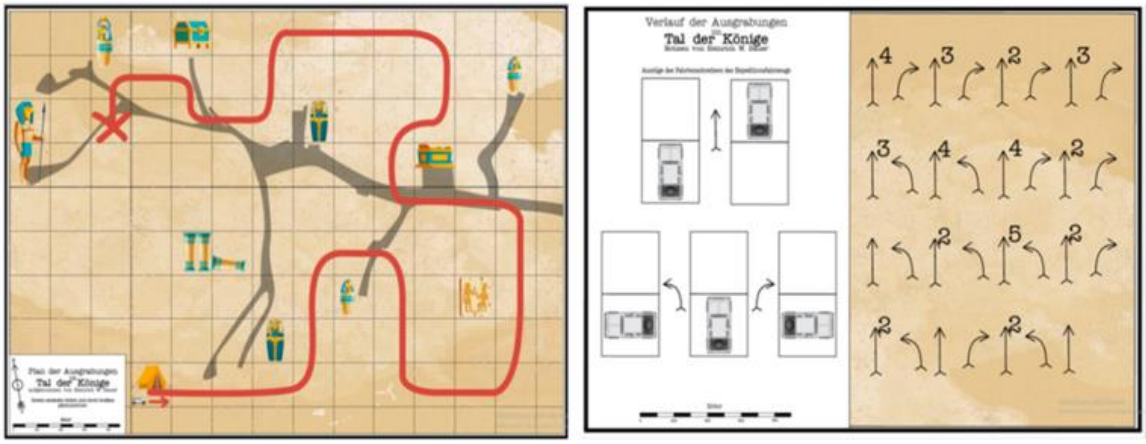

Figure 2. Valley of the Kings troubleshooting problem taken from [4]. Reprinted with permission from IEEE Proceedings.

of these directional arrows were intentionally incorrect, and students were tasked with identifying these errors. Successfully completing the module required students to employ a topographic strategy, involving reasoning and tracing, to align the directions with the route.

The module was integrated into the regular laboratory lecture period, where students worked in pairs to complete the exercise. Following approximately ten minutes of engagement, students were encouraged to share their experiences with the class, stimulating a technical discussion about troubleshooting frameworks and strategies.

Module 2. Circuits: The second troubleshooting module tasked students with repairing two electrical circuits. The first circuit (Figure 3A) consisted of a battery, a diode, and a switch. Two errors were intentionally introduced: the batteries were installed incorrectly and the diode was positioned incorrectly. This exercise was intended to provide students the opportunity to use topographic or an exhaustive troubleshooting strategy. Unlike the initial module, this exercise demanded a degree of domain expertise to grasp the fundamental principles of electricity and circuits, knowledge that our engineers gain from their 1st year physics courses.

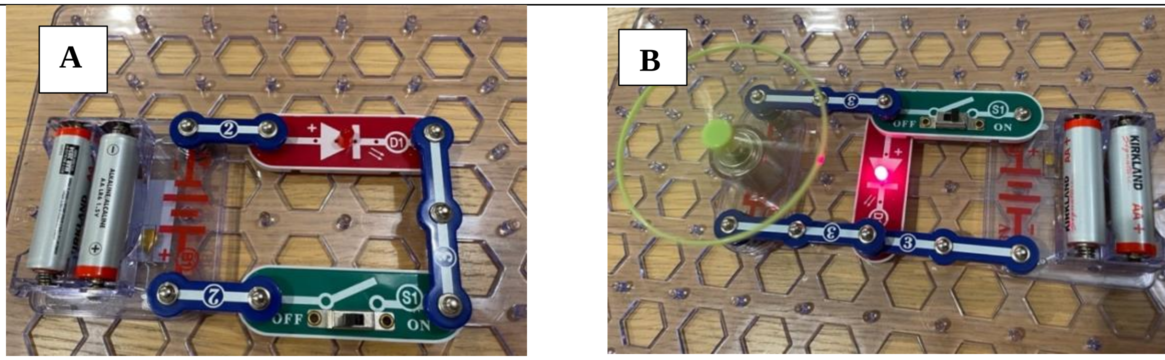

Figure 2. (A) A simple electrical circuit that includes a battery, switch (green), and diode (red). (B) A more complex electrical circuit that requires the diode (red) and electric motor be placed in parallel for both components to be functional.

The second circuit (Figure 3B) posed a significantly greater challenge than the first. In this task, students were instructed to integrate an electric fan motor into the operational circuit. Additional connectors were provided. If the students placed the electric motor in series with the diode and the switch, the circuit would not function. To achieve circuit functionality, the diode and the motor needed to be placed in parallel. This exercise aimed to demonstrate to students that they could not solely rely on isolating, testing, and tracing methods used in the previous example, highlighting the necessity of domain knowledge to tackle the challenge.

During the debrief, the students identified their strategies and techniques. The most common technique used was trial and error. Students who used this technique often gave up after 5 minutes without success. Many students also traced the circuit, while others chunked the circuit by breaking it into components. As a class, we also discussed the analogous nature of electrical circuits and chemical piping configurations and discussed a recent issue with an experiment in the lab which was solved by simply tracing the lines.

Hands-on Troubleshooting Exercise

For assessing troubleshooting skill, we adapted the troubleshooting exercise used the previous semester to evaluate students' troubleshooting proficiency [2]. The exercise comprised an authentic chemical engineering problem derived from a familiar lab experiment, featuring three predetermined errors akin to the approach of Van De Bogard et al. [6]. The task entailed producing hydrogen from carbon monoxide via a reactor system executing the water-gas-shift reaction, using a bench-top plug-flow reactor (see Figure 4).

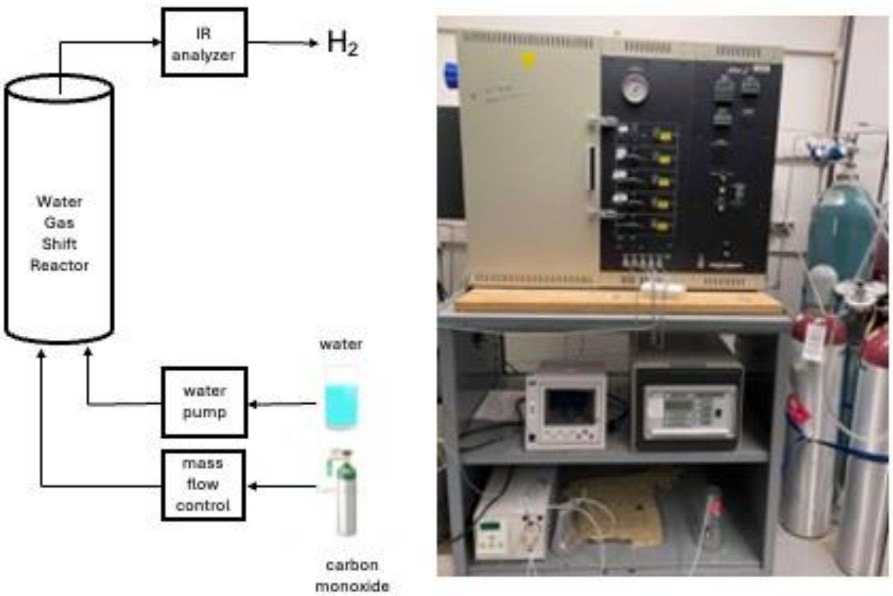

Figure 3. Overview of the experimental setup and an image of the actual setup used by participants in the laboratory [2].

The exercise was completed by teams of two students who entered the lab. Each team received a simplified experimental procedure describing preset initial conditions (e.g., reactor temperature of 250°C and a helium (He) flowrate of 75mL/min) and instructions to complete the task. Teams were allotted 15 minutes to react carbon monoxide and water vapor over the catalyst bed to produce hydrogen. A Teaching Assistant (TA) oversaw the exercise, was responsible for recording observations and enforcing safety protocols, and followed the general guidelines for think-aloud interviews outlined by Ericsson and Simon [9]. The TA was not permitted to answer technical questions nor provide additional clarification about the instructions.

Three authentic and progressively challenging errors were built into the exercise:

1. **3-way valve**: Situated on the reactor's front panel, this valve regulates gas flow into the reaction chamber, offering three settings: closed, vent (to atmosphere), and system. Initially set to vent, students were instructed to "Turn the CO 3-way valve to system," introducing CO into the reactor. Successful troubleshooting necessitated identifying the correct valve, rectifying its position, and enabling gas flow into the reactor.

2. **Carbon monoxide flow**: Carbon monoxide was supplied from a regulated gas cylinder, with gas flow controlled by a mass flow controller. Students were tasked with adjusting the "CO flow through the mass flow controller to 50 ml/min." Initially, the gas cylinder valve remained closed. Effective troubleshooting involved identifying the appropriate gas cylinder, opening its valve, and configuring the mass flow controller. Students were instructed to verify CO flow using the Infrared gas analyzer (IR Analyzer), which monitored both CO and carbon dioxide (CO_2) concentrations in the effluent stream.

3. **Water flow**: Water was supplied via an HPLC pump connected to a 250mL Erlenmeyer flask serving as a water reservoir, intentionally left empty. Successful troubleshooting required identifying the empty water flask and verifying water flow into the reactor. Students were expected to possess the requisite domain knowledge to confirm H_2 production, relying on CO_2 measurement, as hydrogen and CO_2 are generated in a 1:1 mole ratio.

Students successfully completed the exercise when they identified and repaired all three errors.

The TA observational notes formed the basis for an exploratory qualitative analysis of participants' approaches to the troubleshooting exercise. We also compared troubleshooting performance between the students in the current course offering who received troubleshooting training (n=17 teams) and students from a previous course offering who did not (n=6 teams). Previous semester performance of untrained students was referenced from a prior study [2].

Results and Discussion

Troubleshooting Learning Modules

The instructional modules aimed to offer students a safe, low-stakes opportunity to practice their troubleshooting skills and reflect on their strategies. The modules deliberately included minimal instruction to simulate the unpredictable nature of equipment malfunctions and to contrast the structured conditions of assignments.

Initially, students found the Valley of the Kings exercise to be cryptic, but quickly engaged with the material, deciphering directions, and completing the challenge within the 15-minute time limit. Feedback highlighted the use of pattern recognition and tracing, along with systematic testing to identify errors.

The subsequent circuits exercises presented a significant increase in difficulty. All students completed Circuit 1 quickly, using a trace troubleshooting strategy to identify errors. Feedback emphasized the use of the trace method and students drew parallels between circuits and piping systems common in the chemical engineering lab.

Circuit 2 posed a tougher challenge that demanded a deeper understanding of circuit fundamentals. All students initially placed the electric fan motor in series with the diode, which caused the diode to not function due to insufficient voltage. Teams then used tracing and testing to troubleshoot the circuit, with many teams opting trial and error and random component reorganization as frustration set in. Eventually, students began to explore circuits in parallel and this led to success for all but one team.

These troubleshooting strategies mirror observations from the chemical engineering laboratory, where initial failures often prompt a shift from systematic troubleshooting strategies to trial-and-error approaches. Discussions to debrief the exercise revealed that students found this challenge more demanding than the previous two and they recognized the need for domain knowledge to troubleshoot the circuit.

Hands-on Troubleshooting Exercise

Ten out of 17 teams successfully troubleshooted the entire system (see Figure 5). Although sample sizes are small and this study was not a random trial, the results of the water flow error specifically suggest a considerable improvement compared to the previous performance of a student cohort that did not receive training.

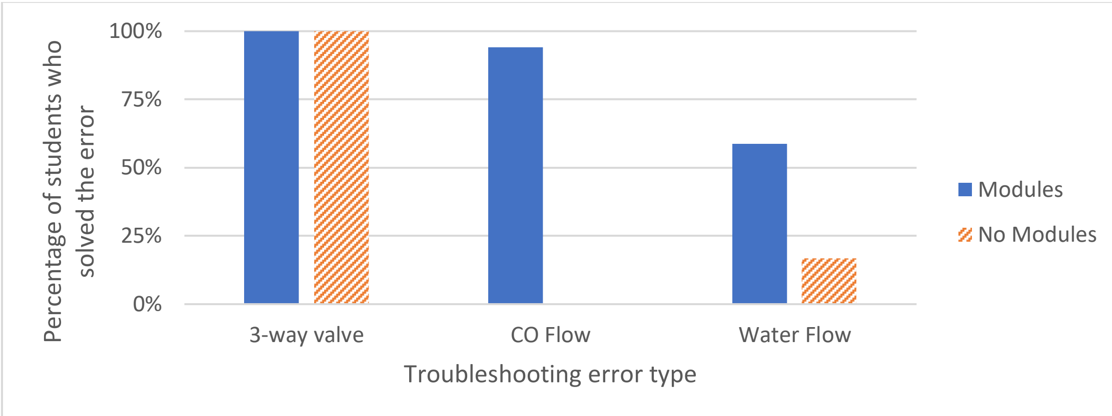

Figure 4. Percentage of student teams that were able to successfully troubleshoot each error type. The solid blue bars represent students who received troubleshooting training and the dashed orange bars represent students who did not receive troubleshooting training. There is no data for the pre-training cohort available for the CO flow due to inconsistencies in the experimental set-up [2].

Reviewing the TA observational data provides further evidence that students were using the troubleshooting strategies and techniques that were discussed in the training modules.

Common Strategies used by Successful Teams: Successful teams used several key troubleshooting strategies discussed and illustrated in the training modules. First, these teams meticulously read the entire problem statement and procedure before initiating error identification and repair. They also used a topographic approach. This strategy includes a comprehensive review of the system and understanding of the equipment involved, followed by tracing the system to pinpoint crucial components like the closed CO cylinder.

Effective communication within teams was also crucial, and teams that engaged in discussion, verbalized their thought processes, or clarified the purpose of each step achieved the greatest success. Notably, successful teams often initiated a repair (e.g., opening the CO valve to system) and then waited to observe or evaluate the effects of their repairs using the IR analyzer before moving to the next issue.

Furthermore, successful teams leveraged their domain expertise to comprehend the system. They referenced reactants and products in the water gas shift reaction to anticipate the presence of H_2 via measurement of CO_2 in the effluent. Constructing these types of conceptual models to identify performance discrepancies is an example of advanced troubleshooting. Additionally, successful teams avoided wasting time on unessential elements of the system, recognizing that the presence of inert gases like helium would not impact performance.

Teams also conducted methodical review of system tubing, which indicates the use of an exhaustive troubleshooting strategy. These teams were more likely to revisit a problem if initial evaluation yielded no improvement, contrasting with less successful teams that proceeded to the next procedural step without persisting. This approach was particularly evident during troubleshooting of the water flow. After turning on the HPLC pump successful teams would wait to ensure that CO_2 levels increased in the effluent, signaling the production of H_2. If CO_2 levels did not increase as expected, these teams would continue their investigation and trace the water lines back to the empty reservoir.

Common Strategies used by Unsuccessful Teams: Overall, most teams exhibited enhanced troubleshooting abilities compared to the prior year [2]. We noted certain trends among the unsuccessful teams. First, unsuccessful teams often allocated excessive time to understanding or addressing non-essential issues. For instance, some teams spent over 5 minutes deliberating what to do with the flow of helium, leaving insufficient time for later stages of the exercise.

Unsuccessful teams often misunderstood the system's operation. Some struggled with CO flow troubleshooting, and, in some instances, teams that ran out of repair ideas would make futile attempts to restore CO flow by manipulating the helium flow. This activity suggests that students lacked the awareness to use tracing to identify the closed CO cylinder. Additionally, familiarity with the equipment led some teams to overlook successful task completion. Despite accurately completing the first two tasks, a few teams expressed concerns about the perceived slow increase in CO rate, suggesting a lack of confidence in their system comprehension.

Frustration, likely stemming from a misunderstanding of system operation, was often observed among struggling teams. In such instances, teams resorted to a haphazard trial-and-error approach, randomly manipulating equipment settings in a desperate bid to troubleshoot. This behavior was more prevalent among teams unfamiliar with the equipment.

Unsuccessful teams also suffered from inadequate communication between team members. Instances occurred where one member proposed an error or repair suggestion, such as asking about the presence of another CO source, only for their partner to ignore the input, leading to the former questioning the value of their contributions and no action being taken. Furthermore, a few teams had one member assume control of the exercise and progress through the instructions without communicating their thought process to their partner, despite explicit instructions from the TA to verbalize their strategies.

Conclusion

This study introduced troubleshooting training modules to instruct students on fundamental troubleshooting processes and strategies, assessing their impact through a hands-on exercise. We observed a considerable improvement in student troubleshooting performance when compared to a previous year's cohort that did not receive training. We plan to complete future work to compare cohorts with and without training more rigorously to see if we still observe the impact on troubleshooting ability.

Furthermore, during the hands-on exercise students demonstrated use of a variety of different troubleshooting strategies, suggesting that the teaching modules had an impact on learning.

Additionally, the hands-on exercise revealed information about the students' level of understanding and comprehension, suggesting its potential as an alternative to written exams for assessing conceptual knowledge and lab proficiency. These findings suggest the efficacy of structured training modules in improving students' troubleshooting skills and conceptual understanding, highlighting their value in engineering education.

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