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The CARE methodology: A new lens for introductory ECE course assessment based on student challenging and rewarding experiences

Aya Mouallem, Stanford University

Aya Mouallem (she/her) is a PhD candidate in Electrical Engineering at Stanford University. She received a BEng in Computer and Communications Engineering from the American University of Beirut. Aya is a graduate research assistant with the Designing Education Lab at Stanford, led by Professor Sheri Sheppard, and her research explores the accessibility of introductory electrical engineering education. She is supported by the Knight-Hennessy Scholarship and the RAISE Doctoral Fellowship.

Prof. Mark Horowitz, Stanford University

Mark Horowitz is the Yahoo! Founders Professor at Stanford University and was chair of the Electrical Engineering Department from 2008 to 2012. He co-founded Rambus, Inc. in 1990 and is a fellow of the IEEE and the ACM and a member of the National Academy of Engineering and the American Academy of Arts and Science. Dr. Horowitz's research interests are quite broad and span using EE and CS analysis methods to problems in molecular biology to creating new design methodologies for analog and digital VLSI circuits

Dr. Sheri Sheppard, Swarthmore College

Sheri D. Sheppard, Ph.D., P.E., is professor of Mechanical Engineering at Stanford University. Besides teaching both undergraduate and graduate design and education related classes at Stanford University, she conducts research on engineering education and

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Abstract

Introductory Electrical and Computer Engineering (ECE) education is of great importance to students interested in exploring the field, as it introduces them to the fundamental conceptual understanding of the governing laws and theories of ECE, as well as to indispensable hands-on lab skills to apply theory in practice. These learning outcomes lay a strong foundational base that proves crucial throughout students' journeys in and beyond academia and in a variety of technical disciplines as well. To ensure these valuable outcomes are met, introductory ECE educators invest significant effort in course assessment and improvement. Such efforts have been documented in literature, including developing new lab tools, incorporating project-based learning, and proposing new course assessment methodologies and educational interventions. Adopting a student-centric lens, we propose a new methodology for early ECE course assessment called CARE, referring to the intersecting areas of the most **C**hallenging **A**nd **R**ewarding **E**xperiences that students have had in line with the main course objectives. This new assessment lens provides a fertile ground to amplify students' rewarding experiences, minimize their unproductive struggle, and preserve healthy challenges that effectively contribute to the students' learning process. In our work, we apply the CARE methodology in studying a population of 42 students enrolled in the introductory ECE course, *ENGR 40M: An Intro to Making: What is EE,* offered at our educational institution, Stanford University. This course was chosen for this study as it emphasizes the importance of integrating theoretical and laboratory exposure to introductory ECE concepts via immersive project-based learning opportunities.

Our main contributions begin with the development of the CARE methodology, its application to assess an introductory ECE course at our academic institution, and the generation of recommendations to improve introductory ECE education at our institution. As a first step in the proposed methodology, we conducted comprehensive needfinding – a human-centered design method – by collecting quantitative and qualitative feedback on the student experience, complemented by instructors' insights. Next, using a grounded theory approach to analyze our data, we uncovered five main areas of intersecting challenging and rewarding experiences, spanning the different theoretical and lab components of the course curriculum. We then offered recommendations to the course instructors to improve the student course experience in every area while being mindful of the effort required and time commitment on the instructors' and students' behalf. Furthermore, we discussed how this methodology can serve as a new approach to satisfy the ABET Criterion 4 for continuous assessment efforts. Finally, we believe that this methodology is generalizable and can scale to assess and improve students' experiences in introductory courses in a variety of engineering disciplines as well.

1. Introduction

1.1. Innovation in ECE Education

Introductory Electrical and Computer Engineering (ECE) education is the essential basis upon which students build their interest in the field, grow their fundamental conceptual understanding of the governing laws and theories, and develop indispensable hands-on lab skills. In general, undergraduate ECE education spans a variety of fields, including electronic hardware, software, and signals and systems. Therefore, the diverse learning outcomes of an undergraduate education in ECE lay a strong foundational base that enables students to pursue lucrative careers in technology in a variety of technical disciplines where there still exists a gap between the number of engineering graduates and the increasing demand for talent by the growing technology industry [1] – [3].

There have been significant efforts to improve undergraduate ECE education using holistic as well as specialized approaches. The Revolutionizing Engineering and Computer Science Departments (RED) grant by the National Science Foundation has supported efforts introducing system-wide curricular improvement, such as the holistic ECE curriculum transformation project at Colorado State University, proposing a new organizational structure that interweaves foundational focus on math and science, creative focus via research and design opportunities, and professional focus on ethics; this is replacing the existing conventional, lecture-style, rigid ECE curriculum [4]. Similar efforts have been funded by the RED initiative at Iowa State University and Virginia Tech [5]. More specific undergraduate ECE education improvement efforts have included pedagogical interventions, such as incorporating project-based learning [4], [6], as well as practical, tool-based interventions, such as the development and introduction of a debugging simulator at Stanford University to gain a better understanding of how students troubleshoot their circuits and debug [7].

ECE education has also seen innovation and experimentation in student assessment and evaluation methods. Direct evaluation methods of student performance and understanding in ECE courses have included mixed exam methods, analysis of final scores, and threshold concept inventories, with generally positive and promising outcomes encouraging long-term adoption [8] – [11].

Some proposed assessment methods have also sought to center the student voice and experience in undergraduate ECE education, in order to invite the students to be active participants in designing and informing the continuous learning process. These approaches have included student-designed assessments in electronics courses and a student-centered teaching methodology [12], [13].

To further expand these recent efforts by educators exploring more student-centric assessment methods, we believe that integrating a student-centric assessment lens can also uncover the students' perceptions toward rewarding and challenging experiences in a course, to effectively inform educators' subsequent interventions and course improvement efforts. Thus, in this work, we aim to explore these experiences and highlight their importance by introducing a new student-centered assessment methodology and providing a walkthrough of its application to an introductory ECE course at our institution.

1.2. The CARE Methodology

Adopting a student-centric lens, we propose a new methodology for early ECE course assessment called CARE. CARE considers the intersecting areas of the most **C**hallenging **A**nd **R**ewarding **E**xperiences that students have had. Furthermore, it considers these experiences in light of the course's learning objectives. This methodology relies on elements of Bloom's and Fink's taxonomies and introduces a new perspective to meet the ABET criteria [14] – [16]. The CARE assessment lens provides a fertile ground to amplify students' rewarding experiences, minimize their unproductive struggles, and preserve healthy challenges that effectively contribute to the students' learning process via interventions informed by the CARE findings.

The CARE methodology is, in fact, a serendipitous product from the first stage of a larger research project exploring the accessibility of ECE education to students who are blind or have low vision. This first stage was focused on taking a needfinding approach to understanding sighted students' experiences in an ECE course. Needfinding provided a rich perspective on these experiences, and it laid the foundation for identifying the framework of "challenging and rewarding" experiences, which is the central organizer of the CARE methodology. The next stage of the larger project, which is not presented in this paper, is to utilize CARE to explore the experiences of a more diverse student group with different visual abilities.

In this paper, we provide a walkthrough of the development and application of the CARE methodology. We cover the data collection and analysis methods, and we explore and discuss the results of applying this proposed lens to assess the experiences of a population of 42 students enrolled in an introductory ECE course offered at our educational institution. We also offer recommendations for course improvements based on our interpretation of our findings. We finally discuss the generalizability of the CARE methodology to different engineering courses and contexts.

Next, we present some existing frameworks that played key roles in the development of the CARE methodology.

1.3. Existing Educational Frameworks

In this section, we provide additional background on several educational frameworks that are used in our work for interpreting and organizing student and faculty input. Often, these frameworks are used in the earlier stages of the course design process to ensure that the learning outcomes are well-defined and will be met. However, in our approach, these frameworks played a critical role in the subsequent assessment phase of the course, as we explain in the *Data Analysis* section.

a. Bloom's Taxonomy

Bloom's taxonomy is a hierarchical framework that describes the cognitive process of a learner [14]. The original taxonomy featured the following six main categories of the aforementioned process: knowledge, comprehension, application, analysis, synthesis, and evaluation. A revised version reframed the six categories as follows: remember, understand, apply, analyze, evaluate, and create. In both versions, the earlier categories in the list correspond to hierarchically lower categories and provide a foundation to build upon to reach and achieve higher categories. In addition, the taxonomy has a dimension exploring four types of knowledge: factual, conceptual, procedural, and metacognitive. This taxonomy can greatly aid educators in clearly defining course goals to achieve desired learning outcomes, and it also helps align the expectations of students and educators for the learning experience in a course. Thus, Bloom's taxonomy can also inform the assessment techniques that educators might use to evaluate whether students have truly grasped the planned learning goals.

In fact, Bloom's taxonomy has been applied in an ECE education context. Meda and Swart used a list of illustrative verbs that serve as synonyms to Bloom's six categories to evaluate whether the objectives of the national, compulsory ECE modules were met in the ECE program at the Central University of Technology in South Africa to identify and recommend improvements for poorly structured learning outcomes in different ECE modules that were offered [17]. Swart and Daneti also relied on Bloom's taxonomy to analyze the learning outcomes of introductory electronics courses in Romania and South Africa [18], with results indicating that the lower hierarchical categories, knowledge and comprehension, encompassed around 58% of the total learning outcomes in both scenarios, while the top two categories, synthesis and evaluation, were represented by only 15% of the learning outcomes. This highlights the need for additional course focus on more complex cognitive problems and exercises.

b. Fink's Taxonomy of Significant Learning

Another educational taxonomy is Fink's, which categorizes the learning experiences into six significant learning outcomes and explores cognitive and affective components of the learning process [15]. The categories are: foundational knowledge, application, integration, human dimension, caring, and learning how to learn. Unlike Bloom's hierarchical structure, Fink's categories are interactive with no precedence of one over the other; rather, the categories may even intersect in a common learning experience. Moreover, Bloom's taxonomy emphasizes cognitive processes, while Fink's additionally touches upon affective learning categories, such as caring and the human dimension. Similar to Bloom's, Fink's significant learning outcomes also help inform the educators' processes as they set goals for a course.

c. ABET Engineering Criteria

In addition to the taxonomies mentioned, the seven engineering criteria of Accreditation Board for Engineering and Technology (ABET) guide educators in the design of curricular offerings and evaluation methods to ensure that engineering programs, including ECE education, meet certain standards [16][19]. Throughout this work, we address specific ABET criteria in relation to our use of the CARE methodology to assess the introductory ECE course under study.

d. Scaffolding and Different Learning Experiences

A **rewarding learning experience** is inherently an educational priority and an ideal outcome for students seeking a new ECE course. In addition, it is probable that **challenges** in the learning process can enrich the student's educational experience and increase the sense of fulfillment that students with a steeper learning curve achieve. This is in line with the idea of educational scaffolding, which recommends that educators build a system of support and guidance for students as they tackle unfamiliar, new, often challenging tasks. Educators would gradually modify the support they are offering, as students gain experience and a better understanding of the techniques used to solve and complete challenging tasks independently [20][21]. In fact, ECE educators have recently shown interest in integrating scaffolding in their course offerings via activities and tools to improve the student learning process in power electronics and with solving RC circuits [22][23].

It is important to note that challenges in scaffolding activities and similar instructional practices are intentionally introduced and controlled by the educator. However, different students might find different offerings of the course challenging at varying levels. It might also be the case that students experience challenges that the educators had not intentionally introduced and are not aware of. In this case, these forms of challenges can create an **unproductive struggle** for students. Given the importance of introductory ECE education and its impact on the academic journey of students, such unhealthy challenges might hinder the students' learning process, weaken their ability to establish a strong foundational knowledge in ECE, and consequently create more barriers to learning than opportunities for rewarding and fulfilling experiences.

1.4. Brief Overview of the Introductory ECE Course Under Study

The introductory ECE course we assess in this work is called *ENGR 40M: An Intro to Making: What is EE*, and we will refer to it as E40M throughout this work for brevity. It was created eight years ago in an attempt to make introductory ECE education more experiential, practical, and fun for students. The course design was guided by two principles:

- Students only learn when they are paying attention, and they only pay attention to material that they are interested in. Thus, the course content was organized around enabling students to build four functional, "useful" projects (e.g., a solar-powered charger), with the overall goal of the course being to enable the students to have fun "making" their own projects after the course.
- Students are always more interested in learning a technique if they have previously struggled with a problem which the technique addresses. Thus, the course uses "just in time" learning to help reinforce the importance of some of the concepts.

The course is offered most academic quarters and has a large enrollment of around 150 to 250 students each quarter. Since E40M also incorporates a lab-intensive component, it requires attentive, supportive teaching staff to make it run successfully. The assessments and course presentation style have evolved since the inception of the course, changing from a lecture-based approach, to lectures with interactive "clicker questions", to a completely active classroom approach where students work in teams during class time. Today, the course adopts a flipped-classroom format. The recorded lectures are available online, and the class time is used for solving example problems and working on homework assignments and projects. During this evolution of the presentation style and use of class time, it also became clear to the instructors that troubleshooting or debugging was a key skill that they needed to help the students learn. Troubleshooting or debugging entails, for instance, figuring out why the project that a student built did not work the way they expected it to. Therefore, the course instructors created additional exercises and tools to support this learning [7].

The assessment methods adopted in E40M include the evaluation of pre-lab and lab work, online quizzes to evaluate students' learning takeaways from the online lectures, homework and debugging problems, and two exams. While the electrical engineering department at our institution has decided not to seek ABET accreditation for its program, the offerings of E40M as an introductory ECE course meet ABET's Criterion 3. This criterion focuses on student outcomes and ensures that the course addresses skills pertaining to analysis, design, communication, ethics, teamwork, experimentation, and continued learning [16]. *Appendix A* provides more information on the offerings of E40M.

In line with continuous efforts to improve the offerings of E40M, we decided to conduct an in-depth assessment of the student experience as the course was running. Therefore, we developed and applied the CARE methodology to study E40M during the Summer 2022 academic quarter, with 42 enrolled students. During that quarter, course enrollment was open to visiting high school students, which resulted in a mix of senior high school students and undergraduate students at our institution taking the course together.

2. Methods

2.1. Data Collection

The first phase of our efforts focused on the collection of data aiming at obtaining profound insights into the student experience in E40M. As such, we relied on conducting comprehensive, student-centric needfinding [24], utilizing a mix of qualitative and quantitative research methods which we describe in this section. As one of the authors of this work, Mouallem, was regularly present in the students' environment and communicated with the students via the course instructor's weekly announcements, she introduced herself during the first lab session as a researcher exploring potential areas of improvement for the course. The data collection efforts lasted for eight weeks, which was the duration of the summer academic quarter. The data were collected in various formats, including typed notes and text entries in surveys. All the data were anonymized by the research team during the data collection stage and prior to the data analysis stage. The data collection methods are described in Table 1, and a timeline of the data collection process is shown in Figure 1. Next, we elaborate more on each method.

Table 1. A summary of the data collection methods used throughout the academic quarter.

Data Collection Method	Amount of Data Collected	Type of Data	Format of Data	Notes
Observation	• 15 hours of observation [1] • 16 pages of recorded data	Qualitative	Handwritten and typed notes	[1] Every lab session was 3 hours long, and there were 6 lab sessions during the academic quarter. The first author observed 5 labs.
Informal Chats With Instructors	Two 30-minute chats with two lab instructors	Qualitative	Handwritten main thoughts and opinions shared by interviewees	One instructor was the current lab instructor. The other instructor was the lab instructor during the previous academic quarter.
Intercepts	4 intercepts	Qualitative	Handwritten summary of the conversation between the first author and the student/instructor initiator	3 intercepts were initiated by students, and 1 intercept was initiated by the lab instructor.
Student Surveys	Six online surveys	Qualitative	Open-ended, typed, short answer responses	This was one survey sent out after every lab. It is available in Appendix A.
	One final reflection survey	• Qualitative • Quantitative	• Short answer responses • Likert-scale or score-based answers • Rank the given options • Select all options that apply	Some questions from this survey instrument are provided in Appendix B.

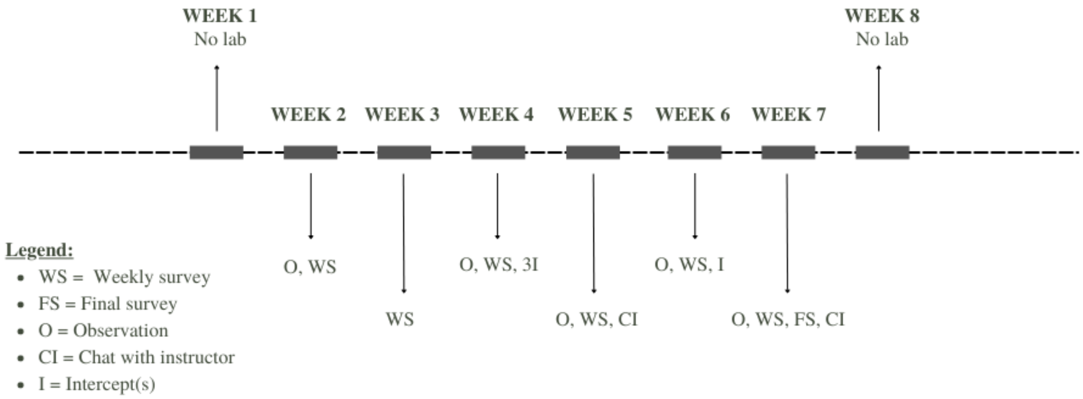


Figure 1. The data collection timeline, utilizing different methods over the eight-week, summer academic quarter.

Observation

Mouallem observed five mandatory laboratory sessions, where students had the option to work independently or in pairs on multiple projects throughout the course. Over the eight-week quarter, there were labs every week excluding the first and last week, and Mouallem did not observe the lab during the third week due to scheduling conflicts. The lab projects spanned different types of hardware, such as the Arduino, and different lab tools, such as the soldering iron and the oscilloscope. Mouallem observed interactions among the students and with instructors, in addition to discussions of the course projects and lab techniques, such as soldering. She also observed the students' use of electronic components and lab tools, and their reactions and approaches to dealing with bugs, errors, and more complex problems and activities. Observing the lab sessions in a weekly manner allowed Mouallem to monitor progress with certain lab skills and recurring difficulties with others, which we discuss in the *Findings* section of the paper. As every lab introduced new concepts and tools, Mouallem decided to observe most labs offered during that quarter, instead of only one.

Intercepts

During the weekly lab observations, Mouallem avoided initiating conversation and asking students questions to avoid the Hawthorne effect [25], as she did not want her presence and questions to influence students' behavior or performance. However, some students asked her questions out of curiosity about different topics, such as any experience she had had with the tools and electronic components that they were using, and her opinions on bugs or errors with which they were struggling. Under such circumstances, while Mouallem did not assist students with their work, she followed up with students on questions regarding their experiences and the areas for which they sought help and feedback. Her follow-up questions did not imply any new thoughts that could bias students' behavior or reactions, but they helped Mouallem gain a better understanding of any challenges that students faced. The lab instructor also approached Mouallem and shared that he was expecting the lab session during Week 6 to generate much more need for the instructor's assistance with debugging than other labs due to the less structured format of its project statement.

Informal chats with instructors

While the CARE methodology is primarily student-centric, we sought out the insight and perspectives of the lab instructors who had led the labs and/or the course lectures over the 2022 Summer quarter, as well as the previous academic quarter. Mouallem had informal conversations with the instructors in-person and virtually, gathering feedback on the instructional preparation process, challenges that the instructors detected in student experiences, and topics with which instructors expected students to grapple. These chats complemented the student perspective with the instructors', which enabled us to cross-evaluate challenging and rewarding experiences that students faced from an instructor's point of view as well, as we discuss in the *Findings* section.

Surveys

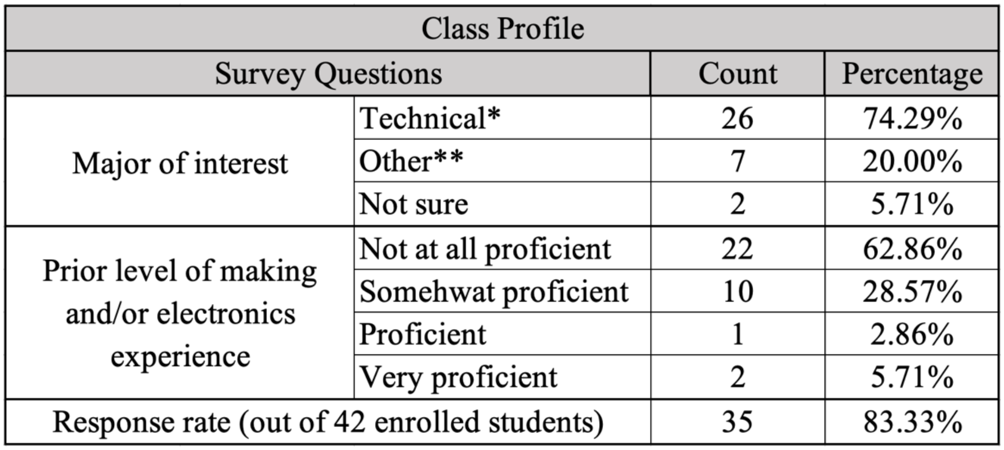
We deployed two types of surveys throughout the course. The first was a recurring survey from Week 2 to Week 7, which asked students the same open-ended questions every week. The survey questions are available in *Appendix B* of this paper.

This weekly survey instrument allowed us to regularly monitor the students' experiences, areas of improvement, and recurring challenges faced. We collected short answer responses to the three questions listed in *Appendix B* every week. Our goal was to identify *all* types of experiences that students had encountered in this course.

In addition to the weekly survey, we deployed a final survey that asked students different closed-ended and open-ended questions. The types of responses to the closed-ended questions included a 5-point Likert scale to rate proficiency in certain skills, ranking most challenging labs, and selecting all options that applied for academic major interests. The open-ended questions accepted long answer responses from students explaining their thoughts on topics such as remaining challenges at the end of the course. Some of the questions on this survey are provided in *Appendix C*.

The final survey questions touched upon students' academic major interests, prior experiences (if any) with making and electronics, motivation to take this introductory ECE course and whether it met the students' expectations, and multiple questions asking students to rate their ability to complete different tasks, use different tools, and understand various concepts after taking the course. The survey also allowed students to expand on any challenges they were still facing at the end of the course. This final survey allowed us to explore in depth the students' interests, prior exposure to ECE, course expectations, learning experiences, and takeaways, in addition to any remaining challenges and final reflections. We provide a brief class profile in Table 2, generated from the final survey data. It is important to highlight the different making and electronics experiences that students had been exposed to prior to taking E40M, in addition to the different academic major interests of the enrolled students. This diversity helped us collect a more representative body of data pertaining to the overall student population’s course experience, rather than narrowing in exclusively on a subset of students who had no prior experience or who had significant prior exposure to ECE and clear interest in the field.

Table 2. E40M class profile of the students during Summer 2022. The data were collected in Week 7 of the course via the final reflection survey.



Class Profile			
Survey Questions		Count	Percentage
Major of interest	Technical*	26	74.29%
	Other**	7	20.00%
	Not sure	2	5.71%
Prior level of making and/or electronics experience	Not at all proficient	22	62.86%
	Somehwat proficient	10	28.57%
	Proficient	1	2.86%
	Very proficient	2	5.71%
Response rate (out of 42 enrolled students)		35	83.33%

*Technical major options in the survey required introductory ECE knowledge and included electrical engineering, computer engineering, mechanical engineering, computer science, aeronautics and astronautics, and symbolic systems.

**Students who chose "Other" provided their fields of interest as text comments. They included business, textiles, and medicine.

Participation in the weekly survey instruments was relatively and consistently high throughout the quarter, with the lowest response rate being 71.4 percent (Week 3 and Week 7) and the average response rate being 84.5 percent. Participation in the final survey was 83.3 percent, consistent with the weekly response rate. This can be attributed to the surveys’ moderate lengths and the instructor’s regular class announcements reminding the students of the survey’s importance.

2.2. Data Analysis

Once all the data were collected using the different aforementioned methods and anonymized, we proceeded with data analysis, which uncovered five main areas of intersecting challenging and rewarding experiences (CAREs).

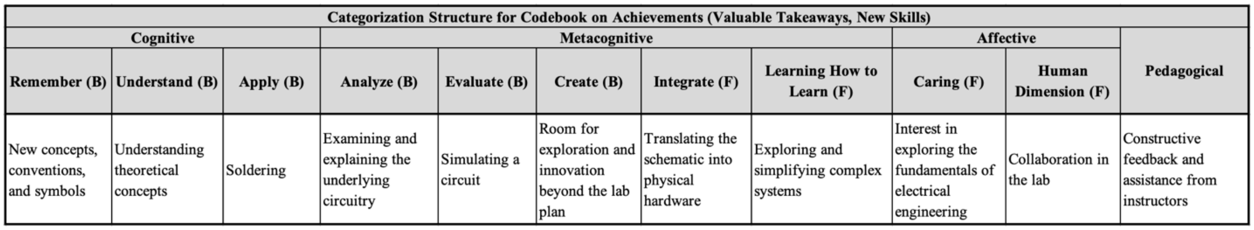
We utilized the grounded theory building approach to generate our findings [26][27]. This approach stresses the discovery and development of theory through the data collection and analysis processes. As this approach relies on inductive reasoning, grounded theorists tend to avoid relying on literature to shape preliminary ideas, expectations, or hypotheses, instead constructing theories and generating all their findings directly from the data itself. In our work, we adopted the grounded theory approach for two main reasons. First, we were seeking as many diverse and different experiences in the course as we could identify. That is in line with what many grounded theorists look for, which is diversity in the studied group rather than uniformity and similarity [28]. Second, we approached the collected data initially with the purpose of exploring student experiences in depth, and we ended up constructing the CARE methodology from our data along the way, as we noticed and identified overlapping challenging and rewarding experiences. Third, the CARE methodology prioritizes generating the hypotheses about students' intersecting challenging and rewarding experiences. The hypotheses can be tested and addressed via recommendations and interventions, but the essence of the effort lies in uncovering the CARE areas first. This is in agreement with the grounded theory approach that focuses on generating the hypotheses more than testing them. Thus, we relied on grounded theory to build our CARE methodology and to generate our CARE findings.

As a first step in the data analysis process, we coded our qualitative data, collected from the open-ended questions on surveys, informal chats with instructors, observation field notes, and intercepts [29]. Coding in this context refers to the practice of systematically labeling and organizing our collected data and representing the data with keywords, or codes, to begin identifying patterns, themes, and relationships among the codes. As we adopted the grounded theory approach, we did not start with a set of expected codes, and we inductively generated our codes while we analyzed our data, in contrast to the deductive approach that relies on a predefined set of codes which are modified and expanded during the analysis process.

We commenced with open coding during our first pass at exploring the data, generating as many codes as possible to represent the qualitative data. We then followed this with two iterations of focused coding. Focused coding entails merging, modifying, and refining the codes to represent clearer and more defined patterns. For example, during focused coding, we classified codes representing students' different attitudes to debugging as sub-codes under one main "debugging" code. While coding, we also wrote memos, reflecting on our evolving thoughts about possible theories and relationships that connect different codes and explaining why students might have experienced what they had.

With this process, we generated 34 different codes and 41 relevant sub-codes addressing different cognitive and affective aspects of the learning experience and the learning environment. The codes represented lab tools, theoretical concepts, emotions, interactions, and different learning experiences. Table 3 displays some codes such as "soldering," "simulating a circuit," and "collaboration in the lab." At this stage, we started to notice and identify which codes were related to challenging experiences, to rewarding experiences, or to both types of experiences simultaneously. This was the first step in categorizing our codes, and it was the first point in our process that paved the way for generating the CARE methodology, using the notions of challenging and rewarding experiences. Thus, we created two codebooks, one including all the codes related to rewarding experiences, and the other including the codes related to challenging experiences. Some codes appeared in both codebooks if their corresponding, collected student data was associated with both types of experiences. Challenging experiences included working with little guidance sometimes, learning how to use the oscilloscope, and exploring and simplifying complex systems. On the other hand, rewarding experiences included building a functional project with a real-life application, having room for additional exploration and innovation beyond the lab plan, and receiving constructive feedback from instructors. As for overlapping challenging and rewarding experiences, we discuss them in detail in the *Findings* section.

Table 3. The categorization structure of the codebook exploring rewarding experiences, along with some generated codes. (B) represents a category from Bloom's taxonomy and (F) represents a category from Fink's taxonomy.



Categorization Structure for Codebook on Achievements (Valuable Takeaways, New Skills)										
Cognitive			**Metacognitive**					**Affective**		**Pedagogical**
Remember (B)	**Understand (B)**	**Apply (B)**	**Analyze (B)**	**Evaluate (B)**	**Create (B)**	**Integrate (F)**	**Learning How to Learn (F)**	**Caring (F)**	**Human Dimension (F)**	
New concepts, conventions, and symbols	Understanding theoretical concepts	Soldering	Examining and explaining the underlying circuitry	Simulating a circuit	Room for exploration and innovation beyond the lab plan	Translating the schematic into physical hardware	Exploring and simplifying complex systems	Interest in exploring the fundamentals of electrical engineering	Collaboration in the lab	Constructive feedback and assistance from instructors

Next, we set up a code categorization structure, and we used the same structure separately for both codebooks, one representing challenging experiences and the other representing rewarding experiences. The purpose of this structure was to analyze, in depth, the types of experiences that students encountered by categorizing them into cognitive, affective, metacognitive, and pedagogical categories. This would help us identify the implications of these challenging and rewarding experiences on different course outcomes at varying hierarchical levels of learning, as highlighted by Bloom's taxonomy, and on different areas of learning, as highlighted by Fink's taxonomy. Consequently, this can allow for a more comprehensive course assessment process. The cognitive categories were derived from Bloom's taxonomy, the metacognitive from Bloom's and Fink's taxonomies, and the affective from Fink's taxonomy. We also added a pedagogical category representing instructional practices. The categorization structure and its categories are provided in Table 3, along with examples of codes from the codebook of rewarding experience. After categorizing our codes, we began to identify main areas of simultaneously challenging and rewarding experiences that impacted the students on multiple levels of the learning process. We discuss the results in the *Findings* section, but first, we describe our validity strategies in the next section.

2.3. Validity

We adopted several practices in an attempt to bolster the validity of our qualitative research process, in line with Johnson's recommendations [30]. First, observing all the labs offered during the academic quarter instead of a few labs allowed us to gain broader knowledge on students' experiences with different tools and concepts. This also helped us connect students' responses in the weekly surveys to their actual observed experiences in class, allowing us to validate some of their responses via field observations. For example, we noticed a significant improvement in the ease of using the soldering iron among many students as the labs progressed, which agreed with the sentiment we sensed throughout the quarter on the weekly surveys about soldering. This practice was defined by Johnson as *conducting extended fieldwork* to allow us to test our hypotheses in the field.

In addition, we adopted multiple forms of triangulation. To incorporate *methods triangulation*, we adopted different data collection methods, including surveys, interviews, and field observation. To integrate *data triangulation*, we collected insight from the students as well as from instructors to collect complementary or distinct perspectives. For example, we asked both, the students and the instructors, about lessons focusing on transistors, and students explained why they struggled with some transistor concepts, while instructors discussed why they anticipated struggle with transistors in the classroom.

Apart from practices to improve the validity of our data collection efforts, we also attempted to improve the validity of our data analysis process. To improve this work's theoretical validity, we incorporated *theory triangulation*, relying on Bloom's taxonomy as well as Fink's taxonomy to analyze the data through a more rigorous educational lens. In addition, we adopted respondents' words verbatim when analyzing their reflections on their emotions, as can be seen in the *Findings* section when we analyze students' attitudes toward debugging. This is in line with Johnson's suggestion to utilize *low-inference descriptors* to preserve respondents' personal and deep meanings.

These approaches aim to increase confidence in the research methods that we adopted in order to arrive at the results, which we explore in the next section.

3. Findings

After using our categorization structure to classify our different codes, we proceeded to identify key areas of simultaneously **C**hallenging **A**nd **R**ewarding **E**xperiences, or CARE areas, giving rise to the CARE methodology structure. As these experiences were derived directly from students' perspectives, they may have or have not been intentional takeaways from the course in the educator's course planning process. This is where the importance of the CARE methodology lies, as it helps identify these potentially overlooked or unidentified experiences by the instructors that may end up having significant influence on the learning experience of the students in this course and on their establishment of a strong foundation in ECE for future coursework.

In this work, we consolidated the overlapping codes into five main CARE areas:

a. Understanding, analysis, and design of circuits
b. Developing hands-on lab skills
c. Exploring and simplifying complex systems independently
d. Debugging
e. Working independently with room for innovation

We explored each area, noting any good instructional or student practices already in effect, as well as areas that could benefit from additional efforts. We then developed recommendations for improvement, focusing on suggestions that are simple and easy to implement without significant demand for resources, as we wanted to be mindful of the effort required and the time commitment on the instructors' and students' behalf. We shared these recommendations with the faculty lead of E40M, who had been teaching it since its inception but was on sabbatical during our research study of the course in Summer 2022. Below, we discuss these recommendations and the faculty lead's feedback.

a. Understanding, analysis, and design of circuits

This area includes understanding theoretical concepts, possessing the required mathematical knowledge, understanding the underlying circuitry of an application, planning the circuit design, translating from circuit schematics to a hands-on hardware set-up, simulating a circuit schematic, and integrating software and hardware elements in a project or exercise.

When students were asked to rate their high-level and in-depth understanding of the course material on the final reflection survey, we noticed a significant difference. This is shown in Table 4, using Microsoft Excel to run a t-test to analyze the collected data. The results reflect a statistically significant difference in the students' perception of a better understanding of the course's general ideas than in-depth concepts, as the p-value obtained was less than the alpha value of 0.05 that was used. As a reference, a p-value less than an alpha of 0.05 indicates that the null hypothesis, which claims that the two outcomes are similar, is rejected, and thus, there is a significant difference.

Apart from quantitative analysis in this area, the codes representing student experiences that we clustered under this area were in line with what instructors expected students to struggle with the most, such as the terminals and current flow in transistors, and the complex representations of signals.

Table 4. The students' evaluation of each of the statements in the table. The scale of the answers ranged from -2 (strongly disagree) to 2 (strongly agree). N=35.

Final survey question: Based on your course experience this summer, to what extent do you agree or disagree with the following statements?			
Statement	**Mean**	**Variance**	**P-Value***
I have good general understanding of the course concepts	1.371	0.476	5.317E-06
I have good in-depth understanding of the course concepts	0.743	0.667	

*A paired t-test was conducted with an alpha value of 0.05.

There are several effective approaches that are already in practice by the E40M course instructors that have been identified as valuable by students. They include weekly homework assignments, multiple weekly office hours, recorded lectures, and an abundance of practice problems. Students particularly appreciated recorded lectures because they were accessible whenever students needed to refresh their memory or slowly explore a certain concept at their own pace, especially when exposed to new theories and multiple steps to solve a problem. While practice problems were highlighted as very helpful, students requested that they be provided throughout the academic quarter and not only around exam time, as students would already be busy with exams for multiple courses simultaneously, with not as much time to tackle these practice problems.

Based on our exploration of the available course material to students, in addition to the faculty lead's feedback on this area, it is probable that reference material to address areas that students find challenging already exist in the available course lecture notes, so students might need regular reminders to check the available material first, in case they are facing difficulties. We still offer some recommendations to further improve this learning area, as follows:

- Monitor challenging concepts via anonymous, weekly minute papers [31]. The instructor could then point students to available course resources addressing these difficulties, and if they're not covered by the course material, the instructor can directly follow up with additional, helpful explanation during the next session
- Provide weekly, targeted, supplementary, and optional practice problems instead of clustered problems around the course exam time
- Use the think-pair-share strategy to encourage discussion of challenges and brainstorming questions among students in lectures and with the instructor [32]

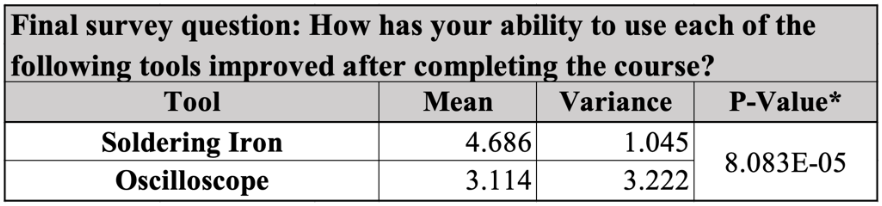
b. Developing hands-on lab skills

Students learn to use different lab tools throughout E40M, such as a signal generator, soldering iron, oscilloscope, and a wire cutter, but we will highlight two tools that students had opposing experiences with, in order to justify our recommendations for improvements in this learning area.

The soldering iron was a tool success story. The iron was introduced during the first lab of the course. Instructors had prepared and made available a soldering guide, and they incorporated soldering into different applications and projects throughout the course. Thus, students had plenty of time to practice soldering, and via our weekly surveys, we were able to monitor the shift in students' perception of soldering from an area of struggle earlier on in the course to an area of pride and achievement as the quarter progressed. In our final survey, we asked students to rate their ability to use different lab tools after completing the course. Students gave the soldering iron the highest score (and lowest variance) among all the lab tools that they were exposed to.

On the other hand, the oscilloscope was a tool room-for-improvement story. The course used the Analog Discovery 2, a compact, USB oscilloscope that generated waveforms on a desktop screen. It was introduced much later in the course during the final lab session. It was incorporated into one project on an electrocardiogram (EKG) application, so students did not have lots of opportunities to practice. In the final survey, students gave the oscilloscope the lowest score (and highest variance) among all the lab tools in terms of their ability to use the tool post-course completion. The resulting p-value of a paired t-test that we ran to compare students' abilities to use the two tools in Table 5 reflects a statistically significant difference.

Table 5. The students' evaluation of each of their tool usage abilities after completing the course. The scale of the answer ranged from 1 (did not improve at all) to 5 (improved a lot). The option "I did not use this tool" was represented with 0. N=35.



Final survey question: How has your ability to use each of the following tools improved after completing the course?			
Tool	**Mean**	**Variance**	**P-Value***
Soldering Iron	4.686	1.045	8.083E-05
Oscilloscope	3.114	3.222	

*A paired t-test was conducted with an alpha value of 0.05.

These two contrasting tool use profiles can be summarized in the following suggestions for improvements in this learning area:

- Reorganize some course content to introduce the lab tool earlier in the course. For example, the oscilloscope could be integrated into an earlier lab session, and students could use it during different labs throughout the course to become familiarized with it in different scenarios and projects. For instance, a student could use the oscilloscope to test their music project earlier on in this course, which is a different scenario than the EKG project that they currently utilize the oscilloscope for.
- Prepare supplementary usage guides and recommend reference material. For example, similar to the soldering guide, a general guide on usage steps for an oscilloscope and commonly encountered waveforms could be offered to students.

- Remind students of the available references and user guides, especially in E40M, as it already offers an abundance of resources which students might not have enough time to explore during stressful periods (such as exam weeks) of the academic quarter. For example, during a lab session, Mouallem observed a student who was struggling with soldering and was advised by the instructor to check the soldering manual. Upon doing that, the student was able to complete his task successfully and quickly.

c. *Exploring and simplifying complex systems independently*

One of the unique characteristics that set E40M apart from other offered courses is the extent to which it integrates real-life applications into the lab projects, such as a solar charger and an electrocardiogram. However, at an introductory ECE level, the design and implementation of such projects independently could be relatively complex, involving different sub-modules and multiple steps.

We observed some effective approaches to this learning area during the lab sessions. For example, the lab manuals usually provided explicit, clear steps to complete a project from start to end. However, during a lab that was relatively unstructured, providing less-than-usual steps to students to create more room for exploration and critical thinking, the lab instructor recommended that students break down the overall problem into subproblems and tackle the latter modularly. Students also regularly discussed among themselves different testing approaches, such as testing one bulb at a time versus an entire row of bulbs at once.

There is still room for improvement in this area, especially in terms of formally teaching students how to independently devise a plan to explore and complete a complex project in this course and in preparation for more advanced ECE courses. The impact of the learning experience can vary based on the learning setting, so we offer different alternatives for individual, group, and student-instructor settings below.

- Introduce analysis methods to tackle complex project statements gradually throughout the course. These methods can be introduced in pre-lab assignments to allow students to internalize their learnings before applying them in the lab.
- Provide worked-through reference examples
- Incorporate homework or lab problems specifically focusing on simplifying a complex project to provide students with space to apply the new analysis methods that they're learning
- Work through an example together during the lab session
- Run small group exercises for students to work together on exploring an example

In discussing this area with the faculty lead, he highlighted that E40M, in its current form, is relatively already saturated with content. As new tools and concepts are introduced to students every week, students often need time to build and apply mental models to learn each new element. Thus, introducing new analysis methods and relevant practice problems will naturally require more time for students to learn and process. Therefore, the faculty lead will investigate balancing the integration of these new suggestions with the current course content. The tradeoff will involve identifying and eliminating some current course material to make room for integrating the improvements.

d. Debugging

Debugging is one of the most essential skills to gain from an introductory ECE course, as it is an indispensable skill during the academic and professional journey of an individual that often remains challenging for programming novices and experts. There have been significant research efforts exploring debugging as a skill, debugging pedagogy, and debugging educational interventions [7][33][34]. Thus, along with the course instructors, we expected that students would struggle with learning how to debug during E40M, especially as the students had varying exposure levels to programming prior to taking this course.

Debugging is mentioned in a few labs and is officially introduced almost halfway into the academic quarter. In the context of E40M, students needed to learn how to debug software code as well as physical circuits using a mix of software and hardware tools, which complicates the debugging process. In the final survey, students were asked to rate their ability to complete the five main objectives of the course, spanning constructing an electronics project, to writing code that controls electronic hardware, to using lab equipment and logical reasoning to build and debug projects. The debugging objective had the lowest average score and the highest variance, indicating the difficulty that students faced with achieving this learning objective.

However, the CARE methodology provided us with valuable insight regarding what students perceived as challenging or rewarding when debugging, and it differed from the planned learning takeaways that instructors had in mind for the debugging aspect of the course.

There are different approaches to debugging that solicit different reactions from students, which instructors may agree or disagree on as intended learning takeaways from the course. These outcomes were extracted from the students' experiences in E40M, as some of them had been exposed to formal debugging education in prior computer science courses. In this course's case, debugging is briefly introduced and not covered in depth due to time constraints, so it is not taught extensively or systematically; rather, the course generally relies on students learning it as they encounter new bugs and errors.

Students who had prior formal debugging education attempted to devise a plan to debug. This is a healthy approach and is the ideal debugging learning scenario. Some students who did not formally learn debugging prior to taking this course attempted to resolve bugs that they encountered in their designs, often by resorting to trial-and-error or seeking the instructor's assistance. While students ended up fixing their errors, this was not the most effective learning experience, as they did not truly internalize a systematic approach to debugging. For example, they did not learn that they needed to isolate subparts of the circuit and test different elements independently when they resorted to trial-and-error, luck, and chance. Therefore, these are two scenarios which resulted in a resolved bug but did not result in the same effective or healthy learning outcome.

Exploring the students' perspectives even more closely, especially through their open-ended responses, we identified course outcomes that were unintended by the instructors. Twenty-two responses on the weekly surveys, from students with differing prior levels of exposure to formal debugging education, used terms with negative connotations to describe the debugging process. Examples of these phrases included "frustrating," "too time-consuming," "I struggled," "I'm still unsure [after submission] whether [the hardware] or my code was problematic," "I struggled with patience," and "it was very complicated." While these types of reactions were expected given the general difficulty of debugging, especially to novice programmers and ECE students, we noticed a trend in students' reactions when they *avoided* debugging. In the latter case, students used the terms "proud" and "achievement" in association with their ability to complete a functional project *on the first try*, *quickly*, *while avoiding* any debugging. These were experiences related to debugging that students labeled as rewarding, whereas, in fact, they were not at all intended takeaways by the instructors.

Despite that, we were able to trace some positive change in students' reactions to debugging, with five student responses highlighting a sense of reward following a frustrating debugging session and successfully detecting and resolving some bugs. However, the general attitude detected in collected responses remained apprehensive to and avoidant of debugging whenever possible.

In summary, we noticed students' general discomfort with bugs, errors, and mistakes and their tendency to avoid the debugging experience rather than embrace it – excluding a select few who grew to appreciate debugging throughout the course and picked up some systematic approaches along the way. Thus, we developed some recommendations addressing cognitive aspects of debugging, in line with Bloom's taxonomy, as well as affective aspects, in line with Fink's taxonomy, in order to improve technical debugging skills and attempt to shift attitudes towards debugging.

Cognitive recommendations:

- Introduce and maintain the use of a debugging simulator to provide students with exercises to practice debugging with feedback [7]

- Incorporate intentional homework exercises on software and hardware debugging that require students to create and document methodical plans

Affective recommendations:

- Discuss the importance of debugging as an unavoidable and indispensable skill for electrical engineering education, lab work, and makerspace experiences
- Acknowledge the frustration and struggle that may result from debugging as expected and natural
- Highlight the character traits needed for successful debugging, including patience, systematic work organization, and attention to detail

When discussing recommendations for this area, the faculty lead of E40M agreed that he expected difficulty in the students' debugging experience during the course, especially as they used new tools to debug. He also noted an additional good practice that is already in effect, as instructors frequently debug together with students to provide guidance and feedback on their debugging processes during office hours and in the lab.

e. Working independently with room for innovation

While E40M is introductory in nature, several students have identified the opportunity to work with little guidance or independently with room for innovation as a simultaneously rewarding and challenging experience.

In fact, this course offers one lab session later in the course, during Week 6, that provides students with the ultimate freedom to be creative with their LED display. This lab has multiple handouts with guidance on incorporating music and different push button functionalities. It also lists some specifications that the final project needs to meet. Students greatly appreciated this lab experience, and this was evident in the final survey, where we asked students to rank the different lab sessions for each of the following categories: most fun, most challenging, and most learned out of. This lab ranked the highest for all these three categories. In terms of room for improvement, students highlighted the steep jump from following detailed instructions and steps in prior lab manuals to suddenly having this wide range of freedom to build something completely from scratch.

Thus, reflecting on students' experiences with this lab's format, we recommend the following for other labs in the future:

- Introduce room for creativity gradually throughout different labs during the academic quarter. For example, one of the earlier lab projects allows students to build a box with mechanical movements controlled by hardware. There could be room for more student creativity in terms of the functionality and the features of the box

- Introduce homework exercises that ask students to independently devise a theoretical lab plan to design, implement, and test a specific project or functionality
- Provide space in homework assignments or in the lab for students to optionally pitch and implement their own additional project specifications or functionalities

When discussing these recommendations with the faculty lead of E40M, he appreciated specific suggestions for certain projects, like the mechanical box lab. He also highlighted that he would explore a balance between two approaches. On one hand, he'll want to ensure that the lab is documented well enough for students to complete the design basics and meet the learning outcomes. On the other hand, the lab can provide additional room, as we recommended, and encourage students to expand their work innovatively.

4. Discussion and Future Work

In this work, we provided a walkthrough of the development of the CARE methodology and its application to assess the introductory ECE course, E40M. We were able to identify, from the students' perspectives, unproductive struggle and unintended, potentially harmful learning outcomes, while also amplifying rewarding experiences. This assessment lens identified several different rewarding and challenging experiences in this course, and there could be a lot of valuable takeaways in further evaluating these two types of experiences separately. However, we found that in exploring the *intersection* of these two types of experiences, we could uncover main areas that mattered most to students in terms of achieving a fulfilling outcome while also being challenging enough to be addressed with recommendations for improvement.

As we featured the faculty lead's feedback on different CARE areas and their relevant recommendations, the faculty lead of E40M expressed that he appreciated the specificity of the resulting recommendations to E40M via the in-depth analysis of the collected data using the CARE methodology. It is worth noting that prior to using the CARE methodology to assess E40M, the instructors had been continuously revising the course over the years. They had relied on exam results and an optional student survey that was available throughout the academic quarter in case any students had feedback. Moreover, at the end of every academic quarter, students had to complete an institutional, general evaluation survey for the courses they were enrolled in, including E40M. The instructors had relied on the results of this survey as well to improve the course offerings. As a result, the instructors tried to implement online debugging activities, changed some of the lecture quizzes, fine-tuned lab content, and incorporated additional practice problems and examples. However, the data from the aforementioned surveys were insufficient for our research, as those surveys only asked for the students' general feedback on the course. In addition, they did not prompt the students to reflect in depth on the different offerings of E40M, especially because the course student survey was optional and available without reminders or deadlines, and the institutional survey was administered only once at the end of the quarter. Therefore, the CARE methodology was the first effort that extensively explored the student perspective and that collected feedback frequently throughout E40M, as shown in Figure 1. Additionally, this was the first effort that identified recommendations to address the specific CARE areas, which highly mattered to students.

We believe that this CARE methodology can help instructors meet the ABET Criterion 4 with a new assessment lens [16]. This criterion requires the use of continuous assessment and evaluation methods to systematically monitor the extent to which student learning outcomes are met and to consequently integrate relevant improvement efforts. Assessment involves the identification and collection of quantitative and/or qualitative data, directly or indirectly in preparation for the evaluation process, which entails interpretation of the assessment data. The CARE methodology meets the requirements of Criterion 4 as follows. Through this methodology, we were able to collect qualitative data via open-ended survey questions and informal chats, as well as quantitative data via score-based survey questions. The CARE lens also allowed for a hybrid direct-indirect assessment process. For example, we were able to indirectly explore students' experiences via observation, and we were able to directly inspect their perception of their learning outcomes via score-based questions asking them to rate their experiences with lab tools and new concepts. In addition, we collected instructor feedback to inform the data analysis process and the resulting recommendations with instructors' insight.

In our next steps, we envision collecting additional feedback from the instructors and students on our suggestions for improvement, and on potential interventions that could be introduced by the instructors as a result. We can analyze this feedback and the impact of interventions via another iteration of the CARE methodology. The complete, iterative CARE methodology is represented in Figure 2, with strong potential to effectively contribute to satisfying the ABET Criterion 4 as a new, continuous assessment approach. In addition, we expect the CARE methodology to uncover more inclusive insight on student experiences when applied to study a more diverse student population, especially informing our larger project efforts investigating the accessibility of ECE education to students with differing visual abilities.

We also believe that the CARE methodology can be generalized to broader engineering education contexts spanning a variety of fields and courses, including introductory and more advanced course offerings. As a generalizable methodology, CARE can generate hypotheses for specific case studies, such as the introductory ECE course that we studied in this paper. In fact, Figure 2 presents a *generalizable* version of the CARE assessment methodology that could be applied in a broader context, beyond ECE education.

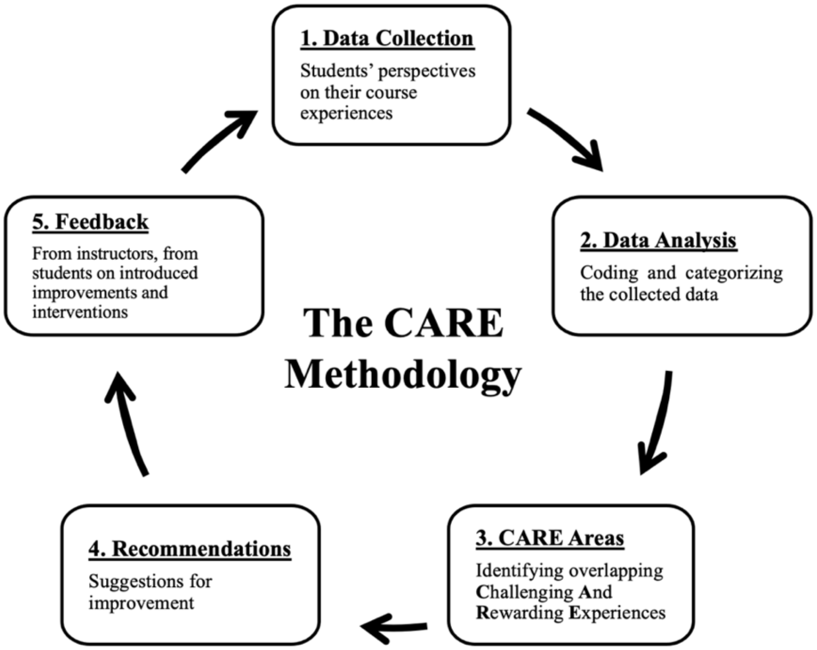


Figure 2. The CARE methodology for continuous course improvement.

5. Conclusion

In this work, we described the development of a new assessment methodology called CARE, exploring the intersection of **C**hallenging **A**nd **R**ewarding **E**xperiences. We applied this assessment lens to an introductory ECE course at Stanford University, analyzing in depth the experiences of 42 students enrolled in this course. After coding and categorizing the collected data, we were able to uncover five main areas for future improvement efforts in the course: (1) understanding, analysis, and design of circuits, (2) developing hands-on lab skills, (3) exploring and simplifying complex systems independently, (4) debugging, and (5) working independently with room for innovation. The CARE methodology enabled us to assess different course experiences that created unnecessary struggle, healthy challenges, and rewarding learning outcomes for students. We are hopeful that this methodology will provide a new, student-centric assessment lens to improve the student experience and truly achieve the intended learning outcomes of an introductory ECE course. We also believe that the CARE methodology is generalizable to broader engineering education contexts, and that it introduces a new approach to satisfy the ABET Criterion 4 on continuous assessment methods.

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References

[1] D. Oguz and K. Oguz, "Perspectives on the Gap Between the Software Industry and the Software Engineering Education," in *IEEE Access*, vol. 7, pp. 117527-117543, 2019, doi: 10.1109/ACCESS.2019.2936660.

[2] S. O. King, "How Electrical Engineering and Computer Engineering Departments are Preparing Undergraduate Students for the New Big Data, Machine Learning, and AI Paradigm: A Three- Model Overview," *2019 IEEE Global Engineering Education Conference (EDUCON)*, Dubai, United Arab Emirates, 2019, pp. 352-356, doi: 10.1109/EDUCON.2019.8725152.

[3] N. Kunicina, A. Zabasta, R. Bruzgiene, N. Dubauskiene, A. Patlins and L. Ribickis, "Student Engagement in Cross-Domain Innovation Development and Its Impact on Learning Outcomes and Career Development in Electrical Engineering," *2019 IEEE Global Engineering Education Conference (EDUCON)*, Dubai, United Arab Emirates, 2019, pp. 661-668, doi: 10.1109/EDUCON.2019.8725269.

[4] A. A. Maciejewski *et al.*, "A Holistic Approach to Transforming Undergraduate Electrical Engineering Education," in *IEEE Access*, vol. 5, pp. 8148-8161, 2017, doi: 10.1109/ACCESS.2017.2690221.

[5] S. Lord *et al.* (Jun. 2017). Talking about a Revolution: Overview of NSF RED Projects. Presented at 2017 ASEE Annu. Conf. & Expo. [Online]. Available: https://peer.asee.org/28903

[6] A. Schuman, L. McNair, T. Martin, and J. Kleiber (Aug. 2022). Project-Based Learning for Second-Year ECE Undergraduate Education. Presented at the 2022 ASEE Annu. Conf. & Expo. [Online]. Available: https://peer.asee.org/40769

[7] A. Fritz, M. Horowitz, and A. Jha. (Jul. 2021). Online, Interactive Tool for Studying How Students Troubleshoot Circuits. Presented at the 2021 ASEE Virtual Annu. Conf. Content Access. [Online]. Available: https://peer.asee.org/37542

[8] W. Wu (Aug. 2022). Using Mixed Exam Methods to Enhance Students Learning for Electronics Courses. Presented at 2022 ASEE Annu. Conf. & Expo. [Online]. Available: https://peer.asee.org/40569

[9] D. Reeping, D. Ozkan, L. McNair and T. Martin, "Stirring up a Special Sauce, A Second Course: Marrying Electrical and Computer Engineering with Threshold Concepts for ECE 101," *2021 IEEE Frontiers in Education Conference (FIE)*, Lincoln, NE, USA, 2021, pp. 1-4, doi: 10.1109/FIE49875.2021.9637254.

[10] J. Scott, M. Peter and A. Harlow, "An electronics Threshold-Concept Inventory," *Proceedings of IEEE International Conference on Teaching, Assessment, and*

Learning for Engineering (TALE) 2012, Hong Kong, China, 2012, pp. T1A-11-T1A-14, doi: 10.1109/TALE.2012.6360366.

[11] R. A. S. Perez, A. Fisher, K. A. Douglas and D. Peroulis, "Assessing Students' Understanding of Solid-State Electronics in the First Introductory-Level ECE Course," *2019 IEEE Frontiers in Education Conference (FIE)*, Covington, KY, USA, 2019, pp. 1-5, doi: 10.1109/FIE43999.2019.9028620.

[12] S. Baghdadchi, T. Meyerott, and P. Hadjipieris. (Aug. 2022). Student-designed assessments in electronic systems and signal processing courses. Presented at 2022 ASEE Annu. Conf. & Expo. [Online]. Available: https://peer.asee.org/40707

[13] Y. Huang and B. Pejcinovic. (Aug. 2022). Implementing Student Centered Teaching Methodology in Electrical and Computer Engineering Courses. Presented at 2022 ASEE Annu. Conf. & Expo. [Online]. Available: https://peer.asee.org/40473

[14] D. R. Krathwohl, "A revision of Bloom's taxonomy: An overview," *Theory into practice*, 2002, no. 4, pp. 212-218, 2002.

[15] L. D. Fink, *Creating significant learning experiences: An integrated approach to designing college courses.* John Wiley & Sons, 2013.

[16] ABET. "Criteria for Accrediting Engineering Programs, 2022 – 2023." ABET.org. https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2022-2023/ (accessed Feb. 12, 2023).

[17] L. Meda and A. J. Swart, "Analysing learning outcomes in an Electrical Engineering curriculum using illustrative verbs derived from Bloom's Taxonomy," *Euro. Journ. Eng. Edu.*, vol. 43, no. 3, pp. 399-412, 2018, doi: 10.1080/03043797.2017.1378169.

[18] A. J. Swart and M. Daneti, "Analyzing Learning Outcomes for Electronic Fundamentals Using Bloom's Taxonomy," *2019 IEEE Global Engineering Education Conference (EDUCON)*, Dubai, United Arab Emirates, 2019, pp. 39-44, doi: 10.1109/EDUCON.2019.8725137.

[19] R. M. Felder and R. Brent, "Designing and teaching courses to satisfy the ABET engineering criteria," *Journ. Eng. Edu.,* vol. 92, no. 1, pp. 7-25, 2003, doi: 10.1002/j.2168-9830.2003.tb00734.x.

[20] J. A. Winn, "Promises and challenges of scaffolded instruction," *Learning Disability Quart.,* vol. 17, no. 1, pp. 89-104, 1994, doi: 10.2307/1511107.

[21] J. Hammond and P. Gibbons, "What is scaffolding?" in *Teachers' Voices: Explicitly Supporting Reading and Writing in the Classroom,* A. Burns and H. de Silva Joyce, Eds., Sydney, Australia: NCELTR, 2005, pp. 8-16.

[22] A. Mehrizi-Sani and R. G. Olsen. (Jun. 2017). Board # 99 : An Intelligent Software Tutor for Scaffolding Solving DC-DC Converter Circuits. Presented at 2017 ASEE Annu. Conf. & Expo. [Online]. Available: https://peer.asee.org/27969.

[23] G. Zavala and C. E. Martinez-Torteya. (Jun. 2020) Students' Abilities to Solve RC Circuits with Cognitive Scaffolding Activities. Presented at 2020 ASEE Virtual Annu. Conf. Content Access, [Online]. Available: https://peer.asee.org/35249.

[24] D. Patnaik and R. Becker, "Needfinding: the why and how of uncovering people's needs," *Design Management Journ. (Former Series),* vol. 10, no. 2, pp. 37-43, 1999, doi: 10.1111/j.1948-7169.1999.tb00250.x.
[25] D. L. Cook, “The Hawthorne effect in educational research," *The Phi Delta Kappan,* vol. 44, no. 3, pp. 116-122, 1962. [Online]. Available: https://www.jstor.org/stable/20342865.
[26] K. Charmaz, “The grounded theory method: An explication and interpretation," in *Contemporary field research*, 1983, pp. 109-126.
[27] A. Strauss and J. Corbin. "Grounded theory methodology: An overview," in *Handbook of qualitative research*, N.K. Denzin and Y. S. Lincoln, Eds., Sage Pub., 1994, pp. 273-285.
[28] R. M. Nieswiadomy and C. Bailey, “Qualitative Research Designs,” in *Foundations of nursing research*, 7th ed. Pearson, 2018.
[29] R. M. Emerson, R. I. Fretz, and L. L. Shaw, "Processing fieldnotes: Coding and memoing," in *Writing ethnographic fieldnotes*, 1995, pp. 142-168.
[30] R. B. Johnson, "Examining the validity structure of qualitative research." *Educ.* vol. 118, no. 2, pp. 282-292, 1997.
[31] D. R. Stead, “A review of the one-minute paper," *Active learning in higher educ.,* vol. 6, no. 2, pp. 118-131, 2005, doi: doi.org/10.1177/1469787405054237.
[32] M. Kaddoura, “Think pair share: A teaching learning strategy to enhance students' critical thinking," *Educ. Research Quart.,* vol. 36, no. 4, pp. 3-24, 2013.
[33] C. Hennessy Elliott, A. Gendreau Chakarov, J. B. Bush, J. Nixon, and M. Recker, "Toward a debugging pedagogy: helping students learn to get unstuck with physical computing systems," in *Information and Learning Sciences,* 2023, doi: 10.1108/ILS-03-2022-0051.
[34] R. McCauley *et al.,* "Debugging: a review of the literature from an educational perspective," *Comp. Sci. Educ.,* vol. 18, no. 2m pp. 67-92, 2008, doi: 10.1080/08993400802114581.

Appendix A – More Information on *ENGR 40M – An Intro to Making: What is EE*

Course Overview

This course provides an introduction to electrical engineering via multiple hands-on lab projects. The course objective is to explore how electronic devices work by breaking down real devices and by allowing students to construct such devices on their own. Undergraduate students typically enroll in this course for 5 units, with the average unit load per academic quarter being 15 units. The course entails three lecture sessions and one lab session every week.

Expected Course Outcomes

By the end of the course, students should be able to do the following:

- Predict the behavior of electrical circuits containing electronic components such as resistors, capacitors, inductors, and transistors.
- Construct such circuits and control their function by running software on a microcontroller.
- Learn and apply effective construction skills to build circuits that can be easily debugged.
- Debug electrical circuits and any relevant software code using logical reasoning with lab equipment and tools.
- Gain a better understanding of how everyday electronic devices work.

Course Content and Activities

The course does not assume a background in electrical engineering. It starts by introducing students to basic circuit elements: resistors, voltage and current sources, and the theoretical concepts (Ohm's law, Kirchhoff's current and voltage laws, KCL and KVL), which allow students to solve for the circuit function. Diodes and solar cells are added to allow students to build a solar powered USB charger. Then, motors, switches, and MOS transistors are added, introducing students to digital logic/systems, and the students build a "useless box" which performs a mechanical movement. Next, students are given an Arduino microcontroller which introduces them to hardware/software co-design and the power of adding a computer to a hardware project. Students, next, looks at different ways to represent data by exploring coding (binary numbers, unary codes) and transforms. With this knowledge, they build a LED display, and either a game to run on the display or a sound visualizer. The final section introduces capacitors, inductors, and op-amp components, and the concept of amplifiers, filters, and Bode plots. Using this knowledge, each student builds an EKG and uses it to measure their own heart signal.

Throughout the course, students learn to solve circuit problems by hand and via circuit simulation software. The course also introduces hands-on lab skills including soldering, hardware programming, and debugging.

Performance Indicators

The course incorporates formative and summative assessment. Students must submit a pre-lab assignment every week prior to the lab session, a lab report after completing the lab, and a weekly homework assignment. Students are also required to take midterm and final exams.

Appendix B – Recurring, Weekly Survey Questions

- What went well for you during the lab, and what were you proud of achieving?

- What concept(s)/tool(s) did you struggle with during the lab? Feel free to elaborate on your experience and what you think could help.
- Did you find any concepts in the class lectures challenging? Feel free to elaborate.

Appendix C – Some of the Final Reflection Survey Questions

- Before taking this course, what was your level of experience with making and/or electronics? That could have been by taking a course, workshop, online training, etc. *Answer options: Not at all proficient, somewhat proficient, proficient, very proficient.*
- Why did you choose to take this course? *Answer format: open-ended, short text response.*
- After taking this course, how confident are you in your ability to complete the following? *Answer options for each of the items below: Not at all, a little, a moderate amount, a lot, a great deal.*
    - Predict the behavior or function of an electronic circuit
    - Construct an electronics project
    - Write code that controls the operation of electronic hardware
    - Debug an electronics project or code
    - Use lab equipment and logical reasoning to build and debug electronic projects
    - Give examples of how circuit elements are used in real-life electronic products
- How has your ability to use each of the following tools improved after completing this course? A*nswer options for each of the items below: I have not used this tool, did not improve at all, somewhat improved, moderately improved, improved a lot, improved a great deal.*
    - Soldering iron
    - Electronic components (transistor, bulb, wires, diodes, etc)
    - Wire cutter
    - Breadboard
    - Circuit simulation platform (eg. EveryCircuit)
    - Arduino board
    - Arduino programming (software) platform
    - Oscilloscope
- Based on your course experience this summer, to what extent do you agree or disagree with the following statements? A*nswer options for each of the items below: Strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, strongly agree.*
    - The time pressure during the lab hindered my learning opportunities.
    - I understand that debugging is one of the main goals of the course.
    - I found debugging frustrating, time-consuming, and did not learn any valuable lessons from it.
    - I found it really helpful to collaborate with my lab mates.
    - I felt that my prior math and science backgrounds were adequate for the course.

  - I needed more time to reflect on and understand the functionality of circuits than lab time.
  - I have good general understanding of the course concepts.
  - I have good in-depth understanding of the course concepts.
- (Optional) What tools/concepts do you still find challenging after completing the course?
  Answer format: open-ended, short text response.