Improving Students' Learning Experiences in Undergraduate Engineering Programs

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Abstract

The increasing demand for computing and other STEM professionals in the United States highlights the need for innovative instructional approaches that improve student learning, retention, and diversity. Despite strong labor market growth and high earning potential in computing-related fields, participation among women, underrepresented minorities, and first-generation college students remains disproportionately low. At the same time, traditional lecture-centered teaching methods often fail to align with rapidly evolving technologies and students' interests in hands-on, real-world problem solving.

This study examines the impact of contextualized, student-centered instruction integrated with maker-centered learning in undergraduate computer science and engineering courses at two university campuses. Guided by the How People Learn (HPL) framework, the project redesigned courses to incorporate active learning, collaborative design projects, maker space training, and participation in Mini Maker Faire events. To explore the effect of the instruction on students' learning outcomes, we designed a demographic questionnaire and a student exit survey, and utilized an existing Life Long Learning (LLL) Scale. The demographic questionnaire and the student exit survey were administered once in a semester at the same time. LLL scale was administered two times, once early in the semester and later towards the completion of the semester. Students' responses to the pre and post LLL Scale were matched and their gain scores were computed. Students' LLL gain scores, their demographic characteristics including gender, ethnicity, and first generation college student status, and their responses to the student exit questionnaires were analyzed.

Results suggest that integrating evidence-based pedagogy with maker culture can enhance students' learning experiences and foster motivation and problem-solving skills. These findings support the continued use of contextualized, student-centered approaches to broaden participation and strengthen persistence in computing-related STEM disciplines.

1. Introduction

Science, Technology, Engineering, and Mathematics (STEM) fields are critical to the United States' economic growth and global competitiveness. Despite their importance, a significant mismatch persists between the supply of STEM-skilled workers and the rising demand for them. According to the Bureau of Labor Statistics (BLS), employment in STEM occupations is projected to grow by 8.1% from 2024 to 2034, significantly faster than the projected 2.7% growth for non-STEM occupations over the same period, and more than double the rate for all occupations combined (3.1%). STEM jobs also command higher wages, with a median annual salary of $103,580 in 2024, more than twice that of non-STEM jobs ($48,000) [1].

Within STEM, rapid growth is expected in high-demand areas such as data science, information security, and other computer- and math-related roles, many of which are forecasted to grow notably faster than the overall STEM average [2]. At the same time, participation in the STEM workforce remains uneven. Reports indicate that although women constitute roughly half of the U.S. population, they represent less than 30% of the STEM workforce, and underrepresented racial and ethnic groups, 27% of the population, hold only about 11% of STEM jobs. These disparities contribute to persistent socioeconomic gaps between men and women as well as between ethnic minorities and European Americans in the broader society.

Specifically for the computer related technology, along with the dramatic advancement of the recently emerged technologies, industry is in great need of graduates with computing-related majors. The U.S. Bureau of Labor Statistics forecasts that, there will be 488,500 more jobs created, which will end up with 1,083,800 total job openings in this category [3]. Due to the aging workforce and emerging techniques [4, 5, 6], industry demand for the qualified graduates with expertise in computer science and computer engineering and technology is tremendous. However, recruitment and retention rates for computing disciplines in the U.S. are dropping, especially for the minority serving institutions. The shortage of the qualified computer-related workforce in the U.S. and the challenges from rapidly growing countries, for example, China and India, have resulted in more computing jobs being shifted abroad every year. This tendency will cause the U.S. to gradually lose its lead in the computer industry. Furthermore, studies have shown that computing classes frequently teach students outdated content that is not relevant to current technologies [7, 8]. As a result, computer related majors have been reported by many institutions to have high drop rates and low enrollment among females and minorities [9, 10].

Advances in computer technology, together with the widespread use of mobile devices and Internet-connected communication platforms, have profoundly transformed daily life and many aspects of modern society. Individuals can now access information instantly, regardless of location. In addition, the increasing availability of low-cost hardware, such as sensors and inexpensive microcontroller boards, has enabled users to design and implement technological solutions without relying on complex tools or direct assistance from experts.

Despite these rapid technological advances, the teaching of college-level computing courses has changed relatively little. This discrepancy has widened the gap between the advanced computing technologies students encounter in their everyday lives and the largely traditional approaches still prevalent in higher education. Many students who choose computing-related majors are motivated by the excitement of innovative applications and real-world problem solving; however, conventional lecture-based instruction often does not align with their learning styles or expectations, leading to reduced engagement and persistence.

To address these challenges, a team of engineers and learning scientists from two universities has collaborated on a federal agency funded project aimed at enhancing student diversity and success in STEM fields. The project focuses on: (1) contextualizing student learning experiences in STEM, and (2) implementing an integrated STEM education approach that develops the skills and knowledge required for success in 21st-century engineering and technology careers. The research objective of the present study is to examine the effectiveness of evidence-based instructional strategies combined with maker-centered learning on students' problem-solving abilities and lifelong learning skills.

Specifically, the project integrates evidence-based pedagogy and maker culture into STEM courses to increase both enrollment and retention of underrepresented students, including women and students from minority backgrounds. By strengthening instructional infrastructure and pedagogical practices at a minority-serving institution, this work aims to enhance teaching quality and, in the long term, contribute positively to the economic competitiveness and societal well-being of the United States.

Makerspaces provide students with a unique environment to be creative and innovative. Students can conduct personally meaningful and practical projects utilizing the tools and machines. The course instructor adopts a more student-centered instruction when the students actively engage in their hands-on activities and utilize the tools and machines in the makerspace. The research team of engineers and learning scientists located on two campuses in the US have received funding from the Department of Education to design and deliver student-centered instruction in their undergraduate courses. The project goals have been to increase the number of students in engineering programs and support them to complete their program. Our engineering faculty utilized the maker activities and worked in collaboration with others to cultivate makers culture in their undergraduate program.

The central research question guiding this study is: What are the effects of contextualized, student-centered instruction in computer science courses on students' learning outcomes and educational experiences? This paper reports the activities with survey results and analysis.

2. Background

The How People Learn (HPL) framework [11] and student-centered instructional strategies informed the design of this project's activities and instructional approaches. The project implements evidence-based pedagogies in core engineering courses to enhance student engagement and develop students' expertise as future makers. Rather than relying on theory-centered instruction alone, the project emphasizes contextualized and student-centered teaching approaches that promote learning through making.

To support this shift, elements of the maker movement and maker culture are integrated into course activities. Students are introduced to maker spaces and maker tools and are guided in their use through structured, hands-on learning experiences. Engineering faculty collaborate with the project team to design new instructional modules that are student-centered and aligned with the HPL framework [11]. Through these experiences, students develop technical competencies, gain confidence in using engineering tools, and begin to identify themselves as "makers" within the engineering community.

How People Learn (HPL) Framework: Research indicates that effective learning environments are characterized by four interrelated dimensions: (a) knowledge-centered, (b) learner-centered, (c) assessment-centered, and (d) community-centered [11]. Evidence-based pedagogies grounded in the HPL framework emphasize active learning, student engagement, and meaningful feedback. Such approaches are inherently learner-oriented and support deeper conceptual understanding, skill development, and the transfer of knowledge to new contexts.

Maker Movement and Maker Culture: The maker movement refers to the growing number of individuals who use do-it-yourself (DIY) and do-it-with-others (DIWO) approaches to design and create technology-based products. As described by techopedia.com, these approaches enable individuals to develop sophisticated devices, such as robotics systems, electronic prototypes, and 3D-printed components, using widely available online resources, including diagrams, written instructions, and video demonstrations. With the accessibility of low-cost hardware and Internet-based resources, individuals with minimal prior experience can design and build functional devices that may be adopted by broader user communities.

Maker culture emphasizes informal, networked, peer-led, and collaborative learning experiences driven by curiosity, creativity, and self-fulfillment [12]. Central to this culture are hands-on skill development and learning through doing within a social environment. These characteristics align closely with the educational goals of engineering and engineering technology programs. As student disengagement from STEM subjects continues to be a challenge in formal educational settings, integrating maker culture into the classroom offers a promising pathway to increase student interest, motivation, and persistence, particularly in computing-related disciplines.

Life-long Learning: Lifelong learning is defined as the ongoing, voluntary, and self-motivated pursuit of knowledge for personal or professional development. It supports social inclusion, active citizenship, personal growth, and workforce competitiveness [13,14]. In engineering careers, rapid advances in hardware, software, and tools require professionals to continuously update their knowledge and skills. Consequently, much of what students learn during their formal education may become outdated or obsolete within a short time frame.

To succeed in this evolving landscape, engineering graduates must develop the capacity for independent learning and adaptability. The nature of engineering practice therefore demands that students cultivate lifelong learning skills, including self-directed learning, problem solving, and intrinsic motivation. This project explicitly targets the development of these competencies through evidence-based, maker-centered instructional approaches.

3. Study Purpose

In this study, we aimed at improving students' learning experiences and outcomes through contextualized and student-centered activities in computer science courses. To answer the main question of the study, maker culture was cultivated in the participating courses in Fall 2022. A Mini Maker Faire at the main institution was held for all students in the college of engineering to showcase their final projects from their courses. These activities were held in the 2022 and 2023 academic year.

4. Study Context: Participating Courses

This project cultivated maker culture in different computer science courses. Below is the description of each course, its teaching context, and how the project potentially impacted the course context.

ELEG 4253 Embedded Systems Design is a three-credit lecture course that introduces students to the architecture, operation, and applications of microcontrollers. Course topics encompass both hardware interfacing and software programming, including CPU addressing and decoding, memory hierarchy, input/output (I/O) interfaces, and interrupt handling. Upon completion of the course, students are able to develop software to control applications that interface with microcontrollers, manage memory and I/O subsystems, and explain key differences among major microcontroller families available in the current market.

Historically, the course was delivered using a traditional, lecture-centered instructional model. Students relied primarily on assigned textbooks, with classroom instruction closely following the organization and taxonomy of the text. Homework assignments were used to reinforce course content, while quizzes and midterm examinations assessed students' conceptual understanding.

Given the rapid pace of advancement in computer and embedded systems technologies, many contemporary applications and design practices are not adequately captured in textbooks. To address this gap, the project enabled the instructor to redesign the course by incorporating student-centered, project-based learning activities. Specifically, students were exposed to competition-style design tasks and guided to identify technical challenges, explore alternative solutions, and implement working prototypes. These hands-on projects were intentionally designed to cultivate a maker culture within the course, encouraging creativity, problem solving, and experiential learning aligned with real-world embedded systems applications.

COMP 3013 Embedded Systems is a three-credit lecture course that introduces students to modern digital design methodologies, microprocessor operations, arithmetic and logic operations, software programming, hardware interfacing, and microprocessor-based system design. Upon successful completion of the course, students are expected to understand the fundamental concepts of microcomputer software architecture and become familiar with microcomputer hardware architectures and interfacing techniques.

Within the redesigned course framework, students engage in hands-on, maker-centered projects in which they design and develop functional products. Project topics may be proposed by students for personal applications or for submission to external competitions, subject to instructor approval to ensure relevance and appropriate scope. Students are encouraged to work collaboratively in teams and are expected to share knowledge and resources both within and across teams. All students receive training in the use of the maker space and maker tools, enabling them to prototype and refine their designs effectively. Student projects are showcased at a Mini Maker Faire, providing opportunities for peer learning, dissemination, and community engagement.

ESET 359 Electronic Instrumentation is a required four-credit, junior-level course. Prerequisites include Embedded Systems Development in C, Digital Electronics, Microcontroller Architecture, Circuit Analysis, and Analog Electronics. The course also serves as a prerequisite for the Control Systems course. Traditionally, ESET 359 was delivered through a conventional format consisting of three hours of lecture and three hours of laboratory instruction each week.

The course introduces students to fundamental concepts in electronic measurement and instrumentation, including measurement system principles, virtual instrumentation using LabVIEW, sensor technologies, analog-to-digital and digital-to-analog conversion, sampling theory and aliasing, digital filter design and analysis, and signal conditioning circuits. Students typically complete seven structured laboratory exercises and a course project in which a LabVIEW- or microcontroller-based measurement system is designed, fabricated, and tested. Upon completion of the course, students are expected to design and implement a complete data acquisition system incorporating sensors, LabVIEW, microcontroller programming, and printed circuit board (PCB) design and fabrication.

As part of this project, ESET 359 was redesigned using evidence-based pedagogical approaches with the integration of maker culture. Student-centered instructional modules and active learning activities were developed to create a high-impact learning environment. Students participated in selected maker events and competitions, with a focus on PCB design, sensor integration, and embedded systems development. Representative student projects included wearable embedded systems, electronic clocks, and autonomous robotic platforms.

The ESET program also sponsors a maker event hosted in the Product Innovation Cellar (PIC), a dedicated space used by ESET students for capstone projects and product development activities. To evaluate the impact of the course redesign, surveys were administered to ESET 359 students at the beginning and end of the semester to assess changes in knowledge, skills, and interest in embedded systems development. Pre- and post-course analyses were conducted and the results were compared with data from CPET surveys to examine relative learning gains and student engagement outcomes.

5. Extra Curriculum to Promote Maker Culture

Robotics clubs and ACM student chapter activities have been established within the authors' departments to support and extend maker-centered learning beyond the classroom. Building on the successful integration of maker culture within the courses proposed in this project, students become familiar with maker tools, practices, and collaborative design processes, positioning them to undertake increasingly sophisticated projects.

Faculty work closely with students to mentor project design and development, and completed projects are showcased at a Mini Maker Faire. These student organizations serve as catalysts for sparking and sustaining interest in STEM disciplines across the College of Engineering, fostering a community of creativity, innovation, and peer learning.

Data and findings collected from students' extracurricular activities are systematically analyzed by learning scientists on the project team. This analysis provides a closed-loop feedback mechanism that informs continuous improvement of both the student organizations and in-class instructional practices, strengthening alignment between curricular and extracurricular maker experiences.

6. Data Collection and Analyses

To explore the impact of the contextualized and student-centered instruction on students' learning outcomes, we asked students to complete a demographic questionnaire, a lifelong learning scale, and a student experience survey. These instruments were administered in the courses in Fall 2022 and Spring 2023. We collected data from courses STEM faculty taught using a demographic questionnaire and the LLL scale, which is in the Appendix. The data collected was used for control purposes.

In Fall 2022 semester, a total of 57 students completed both pre and post LLL and Demographic questionnaire in both campuses.

At Texas A&M University (TAMU) campus, 56 students who enrolled in the ESET 359 Electronic Instrumentation course completed the surveys. Among these 56 students, 22 of them were Latinx (39.28%), 22 of them were Caucasian (39.28%), 7 of them were Asian (12.5%), 2 of them were African American (3.57%), and 2 of them were mixed (3.57%). One student reported their ethnicity as other (1.78%). There were 43 boys (76.78%) and 13 girls (23.21%). 20 of the students at TAMU campus participated in the project activities were first generation college students (35.71%) and 36 of them were not first generation college students (64.28%).

At Prairie View A&M University (PVAMU) campus, 1 student who enrolled in the COMP 3013 Embedded Systems course completed the surveys. This student reported her ethnicity as mixed (100%). She was not a first generation college student (100%).

Major Finding: When we run a paired sample t-test to compare the students' pre and post LLL survey scores, we found that students (N=57, Mpre=3.56, SDpre=0.44, Mpost=3.64, SDpost= 0.42) improved their LLL skills after the semester is completed However this increase was not statistically significant at p=0.05 level (t (56) = 1.6, p=0.11). Cohen's d effect size showed a small group mean difference (ES= 0.212).

In Spring 2023 semester, a total of 69 students completed both pre and post LLL and Demographic questionnaire in both campuses.

At PVAMU campus, 26 students who enrolled in the COMP 3013 Embedded Systems course and 16 students who enrolled in the ELEG 4253 Embedded System Design course completed both surveys. 11 of these students were first generation college student (26.19%) and 31 of them were not first generation college students (73.81%). 39 of these students were African American (88.63%), 2 of them were Asian (0.05%), and 2 of them reported as other for their ethnicities (0.05%). There were 33 boys (75%) and 10 girls (25%).

At TAMU campus, 26 students who enrolled in the ESET 359 Electronic Instrumentation course completed the surveys. 9 of these students were first generation college student (34.61%) and 17 of them were not first generation college students (65.38%). 13 of the students were Caucasian (50%), 7 of them were Latinx (26.92%), 3 of them were Asian (11.53%), and 2 of them were mixed (7.69%). One of the students reported their ethnicity as other (3.84%). There were 23 boys (88.46%) and 3 girls (11.53%) at the TAMU campus.

Major Finding: When we run a paired sample t-test to compare the students' pre and post LLL survey scores, we found that students (N=69, Mpre=3.73, SDpre=0.48, Mpost=3.78, SDpost= 0.58) improved their LLL skills after the semester is completed. However this increase was not statistically significant at p=0.05 level (t (68) = 0.815, p=0.41). Cohen's d effect size showed a very small group mean difference (ES= 0.09).

Students' Lived Experiences in the Courses Participated in the Project in Fall 2022 and Spring 2023.

Similar to the previous year's findings, students described their learning experience in the project courses as "hands-on." A student wrote: "I enjoy the lab the most because it allows me to see hands on what we are learning in lecture."

Students were asked to choose their project topics. Students enjoyed the freedom the project provided to them. One student commented: "I liked most the final project because it was a hands-on design project collaborated with Apple engineers."

Students were pleased with the learning opportunities in the courses. They reported that the course instructors were effective in their teaching. A student commented: "The professor is really good, their explanations are clear." Another student detailed their response as:

"The best thing about the course for me is the level of thoroughness and the effort our course instructor puts in their class to not only have their students understand the course material, but also the effort they have to push the students to further lengths. For example, many of the problems encountered in class can be solved using a mathematical process which can take about 5 minutes, however, keen eyed students can shorten the amount of time they spend solving problems to just a few seconds by analyzing the problem, so long as they truly understand the course material and the problem they are solving."

Students liked the labs, the homework, and the exams in the courses. A student reported:

"I liked how detailed the labs were. It helped that the instructions were in depth because it helped my lab partner and I understand the code better, which helps our overall learning of MATLAB functionality more efficient."

Another student noted: "I liked how the daily quizzes and homeworks prepared the student well for examinations." One of the students commented on the final project: "The final project, it helped me to understand concepts that were more theoretical."

Students reported that they learned many things in the course. For example, "I learned about control systems and the complex intricacies of how to analyze, and simulate them" and "I learned about the importance of control systems in the field that I am going into which is robotics. Almost all robots are a control system that will take in some sort of input and use that input to do a task."

Overall, students enjoyed the course activities and reported positive attitudes and reflections about the instructors.

7. Conclusion

The design and implementation of the contextualized and student-centered instruction (that are student centered and HPL framework informed) was implemented on two university campuses for engineering students. In this paper we reported the summary of our project and described our data collection and analyses from the students. Our project can help improve STEM faculty's awareness of evidence-based pedagogies and willingness of using these pedagogies. Evidence-based maker culture teaching modules that we develop and test can be used in other STEM courses. Our students' learning, interest, and retention in specific subjects were improved, especially for first generation college students. The project can help increase the number of ethnic minority students, particularly minority women, in STEM fields.

8. IRB Approval

The Institutional Review Board (IRB) at PVAMU reviewed the protocol associated with this research and granted it exempt review status, under the exempt review category according to the Code of Federal Regulations (Research involving, but not limited to, educational tests, surveys, or interviews).

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Appendix: Survey Questions

Lifelong Learning Scale

Directions: Please read the below items (16 of them) and indicate your responses for each by circling the appropriate number that best represents your position (1-Never, 2-Rarely, 3-Sometimes, 4-Often, 5-Always or daily).

		Never	**Rarely**	**Sometimes**	**Often**	**Always or daily**
1.	I enjoy intellectual challenges.	1	2	3	4	5
2.	I read for the sake of new learning.	1	2	3	4	5
3.	I converse with others about new things I have learned.	1	2	3	4	5
4.	I like to analyze problems and issues in depth.	1	2	3	4	5
5.	I see myself as a life-long learner.	1	2	3	4	5
6.	My regular activities involve reading.	1	2	3	4	5
7.	My regular activities involve writing.	1	2	3	4	5
8.	I am a self-motivated learner.	1	2	3	4	5
9.	I browse libraries or bookstores for interesting books or magazines.	1	2	3	4	5
10.	I make interesting contributions to discussions in my classes, at work, or with friends.	1	2	3	4	5
11.	My activities involve critical thinking.	1	2	3	4	5
12.	I read for pleasure or entertainment.	1	2	3	4	5
13.	I am curious about many things.	1	2	3	4	5
14.	I pursue a wide range of learning interests.	1	2	3	4	5
15.	I like to learn new things.	1	2	3	4	5
16.	I do a lot of reading that is not required for my classes or job.	1	2	3	4	5