



BUILDING BEYOND THE ROBOT: DISCIPLINARY INTEGRATION IN CHALLENGE-BASED LEARNING

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ABSTRACT

Aim/Purpose	To address the research gap in terms of evidence on students' integration of STEM concepts in challenge-based learning (CBL) in the context of senior high school (SHS) robotics. It also evaluates the extent to which robotics can support students in achieving integrated STEM subject areas through the <i>Situated STEM Learning</i> lens.
Background	Research shows that educational robotics and CBL are effective but overlook the cognitive processes students use to integrate STEM concepts, and there is a lack of qualitative research on their perceptions of STEM integration in robotics. Relying primarily on quantitative data misses crucial insights into student experiences.
Methodology	A descriptive mixed-methods design was employed across two SHS cohorts ($N = 50$). Data were collected using a validated STEM integration assessment rubric, student engineering notebooks, and open-ended feedback questionnaires.
Contribution	Identifies a critical disciplinary imbalance in CBL robotics projects, where technology and engineering often overshadow abstract scientific and mathematical principles. It emphasizes that meaningful integration requires explicit pedagogical scaffolding, not an inherent byproduct of construction.
Findings	Students found CBL highly effective for bridging theory and practice and fostering computational thinking and creative problem-solving. However, project outputs revealed a notable deficiency in the use of scientific reasoning and mathematical calculations to support design decisions, suggesting that these disciplines do not “naturally occur” in robotics without deliberate instructional intervention.

Accepting Editor Dimitar Grozdanov Christozov | Received: January 1, 2026 | Revised: March 1, 2026 | Accepted: March 11, 2026.

Cite as: Jalon, J. B., Jr., & Roleda, L. S. (2026). Building beyond the robot: Disciplinary integration in challenge-based learning. *Journal of Information Technology Education: Research*, 25, Article 10. <https://doi.org/10.28945/5747>

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Recommendations for Practitioners	Pedagogical design should intentionally scaffold Science and Mathematics integration, incorporating scientific justification and mathematical modeling into project milestones. Introductory workshops and project showcases are recommended to address the “beginner’s gap.”
Recommendations for Researchers	Researchers should use a mixed-methods approach to gain a holistic understanding of STEM integration, capturing student perceptions and experiences to provide vital context to quantitative findings.
Impact on Society	This research provides a replicable, evidence-based model for implementing CBL in K-12 robotics to develop critical 21st-century skills. More importantly, it offers a crucial diagnostic insight for STEM educators: the common pitfall of unbalanced disciplinary integration.
Future Research	Use experimental designs, diverse samples, and quantitative studies to assess CBL’s effects on STEM integration. Longitudinal studies are also recommended to track students’ skill development.
Keywords	21st-century skills, Arduino, challenge-based learning, educational robotics, STEM integration

INTRODUCTION

Integrated STEM brings together ideas and methods from two or more STEM disciplines and links them through authentic, real-world applications (Kelley & Knowles, 2016). It exists along a continuum, from multidisciplinary approaches to transdisciplinary models centered on complex problems that transcend traditional subject boundaries (Kelley & Knowles, 2016; Tan et al., 2019). Such transdisciplinary approaches are considered essential for preparing students to address global challenges and to develop interconnected understandings of the world (Roehrig et al., 2021). A key feature of successful STEM integration is the use of meaningful real-world contexts that connect abstract ideas to tangible issues and purposeful learning (Falloon et al., 2020).

Educational robotics (ER), rooted in Papert’s (1993) *Constructionist Learning Theory*, offers one such context by engaging learners in designing and programming tangible artifacts. Numerous studies associate ER with improvements in problem-solving and computational thinking (Çakır et al., 2021; Chevalier et al., 2020; Coufal, 2022; Stewart et al., 2021), collaborative skills (Latip et al., 2020), and positive perceptions of STEM learning and careers (Arís & Orcos, 2019; Chen & Chang, 2018; Shang et al., 2023). However, systematic reviews caution that these outcomes are variable and context-dependent (Darmawansah et al., 2023). Moreover, evidence of engagement or skill development does not necessarily indicate deep or balanced integration across all four STEM disciplines (Roehrig et al., 2021).

A related concern is methodological. Much of the robotics-based STEM literature relies on pretests and posttests, surveys, or final products to evaluate effectiveness (Conde et al., 2020; Darmawansah et al., 2023). While informative, such measures offer limited insight into how students actually connect and apply disciplinary knowledge during the design process (Roehrig et al., 2021). As a result, claims about the integrative power of robotics are often based on outcomes rather than analyses of disciplinary interaction.

Challenge-Based Learning (CBL) has been identified as a key framework for structuring robotics-integrated STEM (Conde et al., 2020). Defined as a model for learning through solving real-world problems (Nichols et al., 2016), CBL is organized around three phases – Engage, Investigate, and Act – through which students define a meaningful challenge, build required knowledge, and implement solutions. Unlike Project-Based Learning or Problem-Based Learning, CBL places stronger emphasis on student-defined challenges and learner agency (Membrillo-Hernández et al., 2019; Nichols et al.,

2016). Studies report that CBL can enhance motivation, collaboration, and applied understanding (Félix-Herrán et al., 2022; Gonçalves et al., 2019; Hernandez et al., 2020). Nevertheless, much of this research is situated in higher education (Conde et al., 2020), and similar to robotics research more broadly, it often evaluates performance outcomes rather than examining patterns of STEM integration. Although perceptions are frequently measured, fewer studies qualitatively explore students' lived experiences of integrating STEM concepts, including the challenges and tensions they encounter (Chen & Chang, 2018; Darmawansah et al., 2023).

Taken together, the literature reveals a clear gap. Despite strong advocacy for robotics and CBL as vehicles for integrated STEM, there is limited qualitative evidence on how secondary students integrate STEM concepts into CBL robotics projects and how students perceive and experience this process. Without such process-oriented analysis, engagement gains may be conflated with meaningful interdisciplinary integration.

This study addresses these gaps by examining STEM integration in a senior high school (SHS) CBL robotics course. Drawing on the Situated STEM Learning perspective, this study critically examines whether the authentic context of robotics, structured through CBL, is sufficient to promote balanced disciplinary integration. By analyzing students' project outputs and reflections, the study provides a process-oriented account of integration in a secondary setting.

The following research questions guided this study:

1. How well, and in what patterns, did the students integrate STEM concepts in their CBL projects?
2. What are the students' perceptions of integrating STEM concepts in robotics CBL, particularly regarding its impact on their understanding and problem-solving abilities?
3. What are the challenges students encountered in integrating STEM into their CBL projects?

CONCEPTUAL FRAMEWORK

Our study was guided by a conceptual framework that integrated *Constructionist Learning Theory*, *Challenge-Based Learning*, and *Situated STEM Learning* to inform the design of the learning environment and the analysis of student outcomes.

Our study drew inspiration from Seymour Papert's (1993) Constructionist Learning Theory, which emphasizes that learning truly shines when students dive into creating meaningful, tangible projects that they can share with others. This idea guided our decision to use robotics as a teaching tool. We wanted to explore the cognitive and practical outcomes of this hands-on learning method, where students build working robots to tackle problems they find interesting. The physical robot served as a representation of abstract STEM concepts, and the process of designing, building, and programming was the core way students gained knowledge. The STEM Integration Assessment Rubric helps us gauge the quality of the robots they build, while analyzing their engineering notebooks gives us a peek into their "learning-by-making" process. This allows us to explore our first research question: *How well, and in what patterns, did the students integrate STEM concepts in their CBL projects?*

While constructionism provided the "why," Challenge-Based Learning (CBL) provided the pedagogical "how." We structured the robotics course around the CBL framework, which consists of three key phases. In the first phase, known as *Engage*, students defined their unique, actionable challenges. This step was essential for investigating how personal ownership influences the learning process. Next, during the *Investigate* phase, the course facilitated the development of foundational knowledge crucial to solving the problems. This scaffolding is vital for student success. Finally, the *Act* phase provided students with the opportunity to design, test, and implement their robotic solutions. During this phase, we gathered key data through engineering notebooks and final projects to evaluate how well students integrated STEM concepts. A key feature of CBL is that it empowers students to define their specific challenges, fostering a profound sense of ownership and personal investment in the

learning process (Membrillo-Hernández et al., 2019). By implementing CBL, the course created a student-centered environment that operationalized constructionist ideals in a structured manner, making it easy to replicate and adapt for future educational settings.

Finally, the *Situated STEM Learning* perspective provides the lens through which this study analyzed the integration of disciplinary knowledge within the robotics tasks. This perspective argues that learning is most effective when situated in authentic, problem-based contexts where disciplinary knowledge is not taught in isolation but is applied synergistically to solve real-world problems (Kelley & Knowles, 2016). ER provides the ultimate situated context, serving as a platform where abstract scientific principles, mathematical calculations, technological tools, and engineering design processes must converge. This framework was appropriate for two major reasons. First, the *Situated STEM Learning* framework considers Engineering Design as a central integrator, providing a systematic approach to solving problems that naturally occur across STEM fields. This helps connect disciplines and offers an authentic context for applying STEM knowledge to solve problems, aligning with *Constructionist Learning Theory* and *CBL*. Second, this framework acknowledges that not all STEM disciplines can be situated in all authentic contexts. Hence, this lens is crucial for interpreting the pattern of STEM integration revealed by the data collected.

METHODOLOGY

RESEARCH DESIGN

We employed a descriptive, mixed-methods design to investigate student learning within a CBL robotics environment. The design was descriptive, aiming to thoroughly document and analyze the integration of STEM disciplines and student perceptions without a control or comparison group (Cresswell & Cresswell, 2023). Moreover, the mixed-method design involved the concurrent collection and analysis of both quantitative and qualitative data to develop a holistic view of the pedagogical approach (Cresswell & Cresswell, 2023). This enabled us to triangulate quantitative proficiency data with qualitative insights from student work and reflections, providing a more comprehensive understanding of the learning process. We collected quantitative data through a panel's ratings of students' STEM integration levels. In contrast, we collected the qualitative data through content analysis of students' engineering notebooks and a thematic analysis of student responses to two open-ended questions. The content analysis of the notebooks provided a detailed explanation of how students integrated STEM concepts into their projects. At the same time, the student perception data offered valuable insight into the overall learning experience.

PARTICIPANTS

Participants in the study were selected through purposive sampling. There were two SHS cohorts, and they were ideal because their voluntary participation indicated a genuine interest in robotics. This intrinsic motivation and established interest ensured deeper engagement, making them a rich source for understanding the student experience (Memon et al., 2025).

The first cohort consisted of 23 males and five females (13 in Grade 11, and 15 in Grade 12), with ages ranging from 16 to 18 years ($M = 17.00$, $SD = 0.69$). Additionally, 23 had no robotics experience before the course implementation. The second cohort consisted of 14 males and eight females (four in grade 11 and 18 in grade 12), with ages ranging from 16 to 18 ($M = 16.80$, $SD = 0.70$). These students were invited because they were planning to integrate robotics into their capstone projects. Moreover, 16 students had no robotics experience before the course implementation.

The sample size reflects the practical realities and ecological validity of school-based research. This sample size can support the intensive, group-based nature of CBL, which requires significant mentorship (Conde et al., 2020) and resources during its interconnected phases. Furthermore, the use of two distinct cohorts enabled the researchers to triangulate their findings and ensure that the identified integration patterns were consistent across student groups.

INSTRUMENTS

Learning context

The school has implemented a trimester academic year, with each term lasting 14 weeks. The 14th week is the final examination week. Hence, we designed the robotics course for 13 weeks, with weekly meetings; each session lasted three hours, equivalent to a regular 3-unit course. The implementation of the CBL in the course was guided by the *RISE Challenge planner* (Challenge Based Learning, n.d.), and students progressed through the three distinct phases. First, in the *Engage* phase (meetings 1-2), they identified a personally relevant challenge they wanted to solve with robotics. They then moved to the *Investigate* phase (meetings 3-6), where they acquired the necessary knowledge and skills by progressing from teacher-guided foundational lessons to independent exploration of (advanced) topics tailored to their project's needs. Finally, in the *Act* phase (meetings 7-13), students designed, built, and programmed their solutions using the Arduino platform, culminating in a presentation to a panel of STEM teachers in the 12th meeting. The last meeting was for reflection on their journey and answering the course feedback questionnaire.

This study had two cycles, each with a different cohort. Additionally, Cycle 1 compressed the activities into nine meetings due to unforeseen class disruptions, such as typhoons and transportation strikes. This resulted in two *Investigate-phase* meetings and five *Act-phase* meetings. Cycle 2 of the course implementation has completed 13 meetings.

Crucially, pedagogical suggestions derived from Cycle 1 findings were intentionally integrated into Cycle 2 implementation, thereby improving the learning experience. To address students' suggestions for more sessions, make-up sessions were conducted to ensure the cohort completed the full 13 meetings as planned. Another finding from Cycle 1 was that students often overlooked integrating scientific and mathematical principles, focusing instead on technology and engineering. To counter this, the teacher in Cycle 2 regularly checked students' engineering notebooks throughout the robotics sessions to ensure they were not only recording their ideas, experiment logs, and observations but also explicitly identifying the STEM concepts they integrated into their projects. This practice prompted students to move beyond simple trial-and-error and apply more deliberate scientific reasoning and mathematical calculations to their designs.

Arduino Uno R3 starter kit

The Arduino Uno R3 Starter Kit was chosen for its cost-effectiveness, flexibility, an accessible open-source environment, ample online resources, and ready availability. Each kit provided students with various robotic components, including, but not limited to, an Arduino Uno board, a 4x4 keypad, active and passive buzzers, a temperature sensor, a humidity sensor, and servo motors, to design, build, and test their solutions for the CBL projects.

STEM integration assessment rubric

This 4-point rubric (Beginner, Developing, Intermediate, Proficient) was used by a panel of STEM teachers to evaluate students' final CBL projects. Table 1 shows the STEM integration rubric. The rubric was developed based on the integrated STEM education framework proposed by Kelley and Knowles (2016) and was validated by a panel of three expert STEM educators to ensure content validity and clarity of the performance descriptors. Inter-rater reliability was established using the intra-class correlation coefficient (ICC), specifically the two-way random-effects model ($ICC(2,k)$).

Table 1. STEM integration rubric

Level/points	Description
Proficient 4	STEM concepts are masterfully integrated, with clear and insightful connections that are essential to the solution's design, functionality, and overall success.
Intermediate 3	STEM concepts are solidly integrated, providing a notable improvement to the solution's design. The connections are clear and show a good understanding of STEM principles.
Developing 2	There is an attempt at STEM integration, but it is superficial and does not significantly contribute to the solution. Connections are basic or fragmented.
Beginner 1	The solution shows little to no evidence of STEM integration. STEM components are isolated, unconnected, and do not contribute to the solution's design or function.

Student course feedback questionnaire (CFQ)

The CFQ consisted of two open-ended questions designed to gather rich, narrative data directly regarding the students' perceptions of their STEM integration experiences. The following were the questions asked:

1. How did this integration enhance your understanding and problem-solving abilities?
2. If you encountered challenges in integrating STEM concepts, can you describe them and suggest ways to improve this integration?

Student engineering notebook

Each group had a notebook they used to meticulously record their ideas, notes, experiment logs, and observations throughout the robotics sessions. They were also asked to write the STEM concepts they integrated into their CBL projects.

DATA COLLECTION AND DATA ANALYSIS

For Research Question 1, a panel of STEM teachers used the STEM integration rubric to evaluate student projects during their final presentations. To assess reliability, the two-way random-effects Intraclass Correlation Coefficient model [ICC(2,k)] was used, as suggested by Koo and Li (2016).

To provide context, a content analysis of students' engineering notebooks identified the frequency and context of STEM concepts in their work. It also revealed patterns in how students integrated STEM disciplines. Findings were interpreted through the *Situated STEM Learning* lens.

For Research Questions 2 and 3, a qualitative approach was used to understand students' perceptions of integrating STEM concepts in CBL robotics. Student responses to the two open-ended questions were analyzed thematically (Braun & Clarke, 2021) to identify patterns in their perceptions of STEM integration and the challenges they encountered.

FINDINGS

CYCLE 1

There were five groups in Cycle 1, and their CBL projects were a mobile car trash robot (Group 1), an automated watering robot (Group 2), a monitoring plant device that sends information via the internet (Group 3), a robot that can pick trash (Group 4), and a robot that cleans liquid spills (Group 5). Examples of the projects are shown in Figure 1.

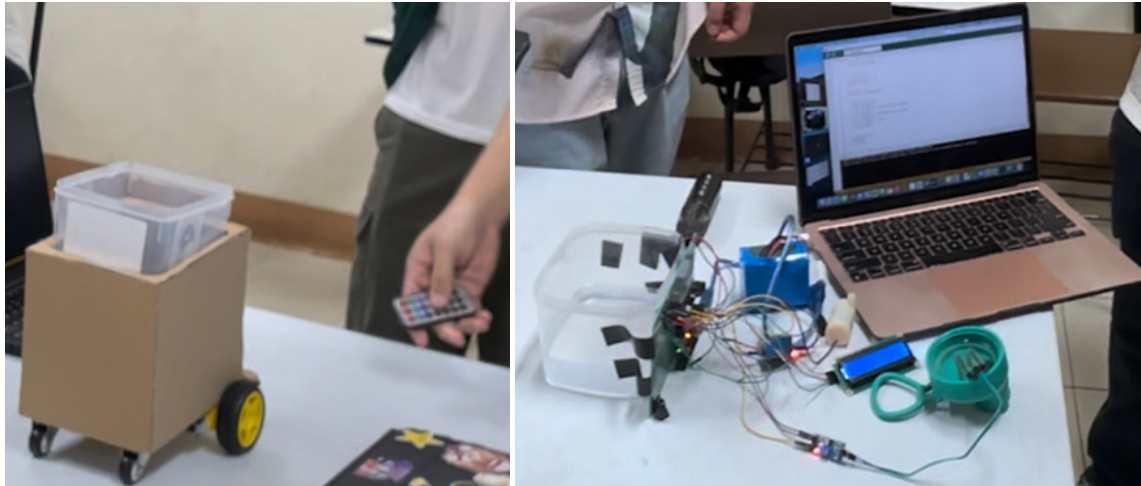


Figure 1. Cycle 1 sample CBL projects
(left, trashbot; right, autonomous watering device)

How well, and in what patterns, did the students integrate STEM concepts in their CBL projects?

Overall, the students demonstrated an intermediate to proficient level of STEM integration ($M = 3.33$; $SD = 0.85$). As shown in Figure 2, Groups 3 and 4 demonstrated exemplary proficiency in integration. Followed by Group 2, which showed consistent strong integration. Group 5’s rating suggested intermediate and solid integration. Group 1 scored lowest, indicating superficial STEM integration that did not significantly contribute to their project. The computed $ICC(2,k)$ was 0.863, indicating strong inter-rater reliability among the three teacher-judges and confirming the validity of these positive findings. However, content analysis revealed a clear disciplinary pattern: Engineering and Technology were highly represented, while Science and especially Mathematics were minimally integrated.

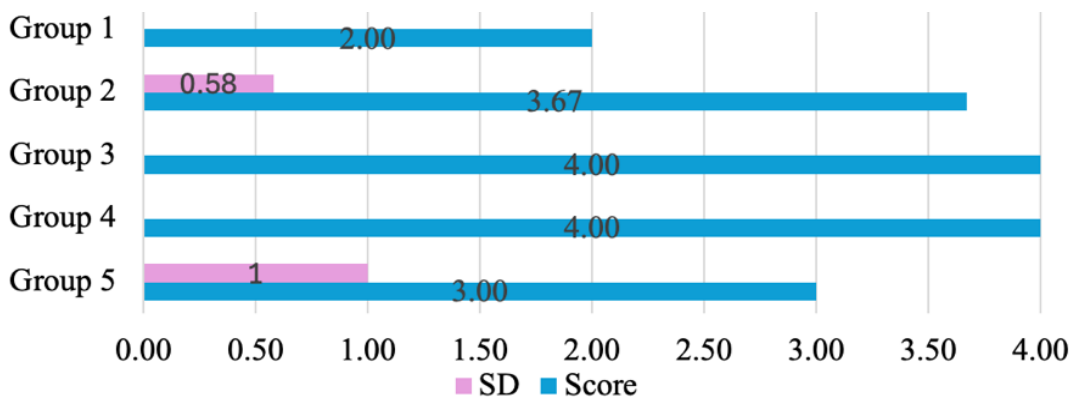


Figure 2. Cycle 1 judges’ ratings

To examine disciplinary patterns, we identified 16 entries from all the groups’ engineering notebooks for content analysis. Table 2 shows the frequency and percentage of STEM disciplines students integrated into their CBL projects. The descriptions of the categories were based on Kelley and Knowles’ (2016) Situated STEM Learning framework.

Table 2. Cycle 1 content analysis results of the students' STEM integration entries

Discipline	Description	Frequency	Percentage
Science	Application of scientific principles to justify a design choice	4	25%
Technology	Use of digital tools, software, or materials related to engineering	13	81%
Engineering	Evidence of applying the engineering design process (EDP)	15	94%
Mathematics	Mathematical concepts, equations, or calculations	1	6%

The students were highly engaged in the engineering design process (EDP), as evidenced by 94% of their submissions indicating this involvement. This was especially noticeable in various EDP activities. For example, in prototyping and iteration, Group 2 advanced from their initial prototype to a second, improved version, while Group 5 shifted their idea from a robot vacuum to a mopping robot after recognizing the impracticality of their original design. In terms of construction and assembly, numerous entries emphasized the building phase, such as Group 1 explaining their process of cutting chassis boards, and both Groups 1 and 5 describing the wiring of their components. Regarding problem-solving, Group 1 demonstrated their troubleshooting during wiring, and Group 5 offered a detailed analysis of the different challenges they encountered, including programming and construction. Overall, it is evident that they understood the steps necessary to create a solution.

Technology integration was also strong, with 81% effectively identifying and detailing the necessary components. For example, Group 2 highlighted the use of a soil moisture sensor, a motorized pump, and a liquid crystal display (LCD) to display sensor data. Similarly, Group 3 incorporated water and pH level sensors into their designs. This reflects a notable strength among the students, as they seemed confident in programming and applying various electrical components. They clearly appreciated the role these technologies play in developing their solutions.

Technology integration was also strong, appearing in 81% of entries. Although some groups referenced scientific ideas, they often failed to clearly explain or justify their design decisions using scientific logic. For instance, Group 5's engineering notebook entries seldom cited any scientific principles, even when discussing topics such as sensors or power. Group 2 mentioned soil moisture but did not elaborate on the concept, suggesting a basic understanding of its significance for plant health. However, they did not clearly explain the scientific reasoning behind it or its impact on their design. Conversely, Group 3 performed better by discussing pH levels, irrigation, and crop yield, demonstrating a clear understanding of the science involved, though they still lacked a detailed justification for their decisions.

Mathematics was the least represented discipline, appearing in only 6% of entries. Only Group 3 highlighted significant, measurable factors such as water level and pH. Although this demonstrated some awareness of math's importance, none of the groups included actual calculations or established benchmarks. This reveals a notable deficiency in students' tendency or capability to incorporate mathematical concepts into their design work. Students could improve their projects by calculating elements such as water volume based on pump speed, determining electrical factors like voltage and resistance for circuit operations, or even designing frames or covers for their projects. It seems that students may have prioritized the practical functionality of their designs over the detailed calculations involved. This lack of mathematical application could hinder their ability to measure design elements, interpret data, and effectively refine their solutions.

What are the students' perceptions of integrating STEM concepts in robotics CBL, particularly its impact on their understanding and problem-solving abilities?

Three distinct ways were identified through the thematic analysis of the Student CFQ responses, which examined their perceptions of how STEM integration in the CBL environment enhanced their understanding and problem-solving skills: (1) bridging the gap between theoretical knowledge and practical application, (2) developing computational and analytical thinking, and (3) encouraging reflection, innovation, and creative problem-solving. These are elaborated in Table 3.

Table 3. Thematic analysis result of the students' perceptions in Cycle 1

Theme	Description	Code
Bridging the gap between theoretical knowledge and practical application	Students connect theory with practice, gaining a deeper understanding of disciplines and developing skills in analyzing challenges and devising solutions.	Applying STEM concepts to understand a scenario/problem. Connecting STEM concepts to understand a scenario. Gives an opportunity to apply prior knowledge to solve problems.
Developing computational and analytical thinking	Enhances students' ability to analyze problems, think logically, and troubleshoot effectively.	Introduced students to analytical/computational thinking skills/programming/coding/debugging process.
Encouraging reflection, innovation, and creative problem-solving	Encourages students to reflect, think creatively, adapt to challenges, and develop innovative approaches to problem-solving when designing and implementing projects.	Helps students think of innovative /creative methods/solutions. Encourages students to research ideas. Encourages reflection to improve understanding and problem-solving.

Bridging the gap between theoretical knowledge and practical application. STEM integration significantly enhanced understanding by creating a direct bridge between theoretical knowledge and practical application. Student 1 shared, *"Through the course activities, I was able to integrate my knowledge in science to our CBL project by comprehending the relation of soil pH level to the health of the soil in terms of keeping plant life alive."* Student 12 said, *"earned more about the breadboard and how it works which was useful in my [Physics laboratory] class."* This aligns with the study of Félix-Herrán et al. (2019), which stated that CBL robotics enabled students to move beyond passive learning and actively engage with STEM concepts through hands-on projects and real-world problem-solving. This integration fostered a deeper, more meaningful understanding as students saw firsthand how theoretical concepts translate into functional solutions.

Developing computational and analytical thinking. This theme demonstrates that STEM integration cultivates the ability to analyze problems, think logically, and troubleshoot effectively, ultimately enhancing students' problem-solving abilities. For instance, Student 7 shared, *"By learning Arduino, we are introduced to the field of engineering, which promotes STEM concepts with analytical and computational thinking skills. It also invokes mechanical skills by engaging in hands-on activities."* Students acknowledged that the STEM-integrated robotics curriculum introduced them to logical and algorithmic thinking, which are essential for problem-solving. Learning computational thinking skills, such as problem decomposition and pattern recognition, enabled students to approach challenges with a structured, logical mindset. Furthermore, the iterative coding and debugging process honed their problem-solving abilities, corroborating the findings of Çakır et al. (2021) and reinforcing the idea that computational and analytical thinking are fundamental to effective problem-solving in STEM fields.

Encouraging reflection, innovation, and creative problem-solving. STEM integration in CBL robotics encourages students to actively reflect, explore, innovate, and think critically as they design and implement projects. Student 17 exemplified this, stating, *“When making our final robot, I found myself having to continually innovate using unorthodox methods in order to get the robot to work. By being flexible and creative with my solutions, I was able to overcome any obstacle I encountered.”* Consistent with this, Arís and Orcos (2019) found a correlation between creativity and students’ solution-seeking behaviors, their perceived utility of robotics for future applications, and their ability to connect diverse curricular content.

What challenges do students encounter in integrating STEM into their CBL projects?

Moreover, the students’ path to cognitive growth was not straightforward; it was forged by overcoming two significant hurdles as described in Table 4. The first was a “lack of prior experience and knowledge in robotics,” and the second was “time constraints affecting learning and STEM integration.”

Table 4. Students’ challenges in STEM integration

Theme	Description	Code
Lack of prior experience and knowledge in robotics	Students struggled due to a limited background in robotics, programming, or circuits.	No robotics experience New to physical Arduino robotics kit Limited knowledge of possible robotics applications Showcase session at the beginning of the course
Time constraints affecting learning and STEM integration	Students found time limitations challenging and suggested improvements.	Time is limited Time is wasted due to waiting More sessions for programming/building

Lack of prior experience and knowledge in robotics. This theme highlights a frequent issue in STEM education, particularly in fast-changing areas like robotics: the “beginner’s gap.” Students often lack the essential knowledge and hands-on experience needed to tackle complex projects effectively. Student 4 mentioned, *“Having no prior robotics experience, I initially found it difficult, but I was able to keep up and join in the activities. Being around experienced individuals also made my learning much easier.”* Student 6 noted, *“One of the challenges we faced was the initial difficulty in understanding and assembling the Arduino components. For many of us, it was our first encounter with such hardware, and programming presented a steep learning curve.”* The students’ feedback indicated a clear feeling of being overwhelmed by the unfamiliarity of robotics. Transitioning from theoretical learning to practical application, especially with new tools like Arduino kits, is a major step. The difficulty in generating project ideas further underscores this lack of contextual understanding. They proposed helping with access to additional resources (such as purchasing locations), showing example Arduino projects at the beginning, and organizing field trips to close this gap. Ultimately, their suggestions stress the importance of structuring learning experiences, providing clear routes for students to gain foundational knowledge and gradually build their skills.

Time constraints affecting learning and STEM integration. This theme emphasizes how the limited time available significantly affected students’ ability to effectively integrate STEM concepts. Many students faced difficulties learning robotics due to time constraints, especially when moving from theoretical instruction to practical work with physical Arduino kits. For example, Student 8 mentioned, *“Arduino is a very technical platform that I feel three hours every week cannot sufficiently cover.”* Others encountered challenges because class time was not always used efficiently, such as waiting for late

group members or dealing with logistical problems like improper material handling. Student 16 noted, “I felt that the time was too long, and much time was wasted. Many of the ERC members would be late ...” These time constraints led to a stressful environment, preventing them from fully engaging with the learning process and completing their projects. During meeting 6, the researcher noticed that the groups were at very different stages of their projects. Additionally, meetings were cut down to nine due to class disruptions. The students’ feedback underscored the need for better time management and more sessions to create a more productive and less stressful learning experience.

CYCLE 2

Six groups presented their CBL project to three STEM teacher-judges. Their projects were a weather monitoring airplane (Group 1), a robot that motivates and teach youngsters about waste segregation (Group 2), a remote controlled search and rescue robot (Group 3), a synthesizer that allows control over parameters like volume, pitch, and modulation (Group 4), a drone medical courier with a temperature sensor (Group 5), and a heart rate monitoring device that sends the details of the nearest hospital relative to the user (Group 6). Figure 3 shows two of the CBL projects.

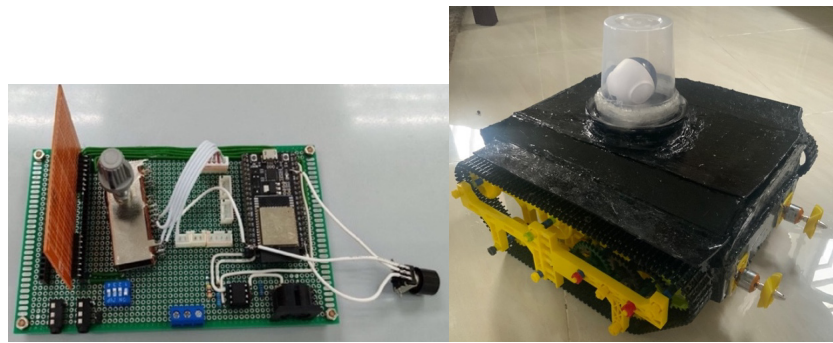


Figure 3. Cycle 2 sample CBL projects (left, Arduino synthesizer; right, rescue robot)

How well, and in what patterns, did the students integrate STEM concepts in their CBL projects?

Overall, the students demonstrated an intermediate to proficient level of STEM integration ($M = 3.50, SD = 0.55$). The $ICC(2,k)$ was calculated to be 0.630, indicating moderate inter-rater reliability. Specifically, Groups 3 and 4 demonstrated exemplary proficiency, with their STEM concepts well-integrated, significantly enhancing project functionality. Followed by Groups 2 and 5, who also demonstrated strong STEM integration. Group 6 showed almost effective integration of STEM concepts, whereas Group 1 showed little to no evidence of integration. Similar to Cycle 1, content analysis revealed a disciplinary pattern in which Engineering and Technology were most frequently integrated, while Science and Mathematics were less consistently applied.

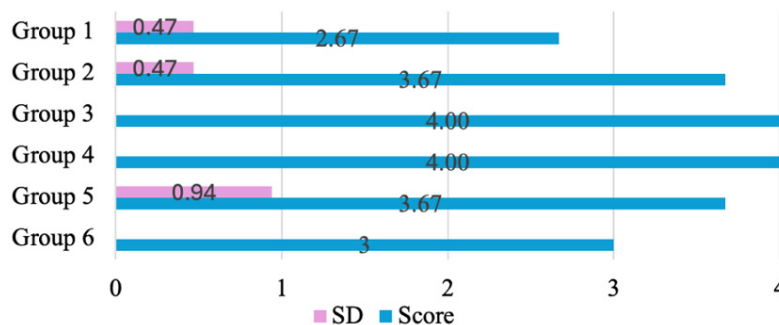


Figure 4. Cycle 2 judges’ ratings

Twenty entries from the student engineering notebooks were identified and analyzed as evidence of STEM integration for content analysis. Table 5 summarizes the frequencies with which specific disciplines were integrated. The trend is similar to Cycle 1, with engineering and technology the most frequently appearing disciplines and science and mathematics the least.

Table 5. Cycle 2 content analysis results of the students' STEM integration entries

Discipline	Description	Frequency	Percentage
Science	Application of scientific principles to justify a design choice	6	30%
Technology	Use of digital tools, software, or materials related to engineering	17	85%
Engineering	Evidence of applying the engineering design process (EDP)	18	90%
Mathematics	Mathematical concepts, equations, or calculations	7	35%

The engineering notebooks clearly showed that students are adeptly applying engineering principles, particularly in prototyping, testing, troubleshooting, and enhancing their work. This practical approach has become a core aspect of their activities. For example, Group 3's notebooks highlighted a strong alignment with the engineering design process (EDP). They recorded tasks such as connecting servos to the ESP32 and resolving connection issues, demonstrating their initial efforts in engineering and prototyping. They also effectively pinpointed the root causes of design failures and used gear ratios in their decision-making. Group 4 focused on selecting appropriate components and provided critiques of their circuit designs, demonstrating their ability to refine their designs and understand the consequences of their decisions. In contrast, Group 5's entries displayed their problem-solving and testing skills through iterative design. They addressed issues with the Subscriber Identity Module (SIM) and conducted ongoing testing to improve their designs.

Technology integration was a key focus, appearing in 85% of the entries. For example, Group 3 effectively used microcontrollers, motors, sensors, and wireless communication in their projects. Likewise, Group 4 consistently integrated components such as microcontrollers, optocouplers, capacitors, and resistors in their synthesizer design. Overall, students demonstrated strong comfort and skill in selecting and combining various technological tools and components to develop their solutions, demonstrating impressive practical abilities with modern engineering hardware and software.

Mathematical concepts were present in 35% of the entries, mainly in the form of simple calculations or numerical data, rather than in complex modeling, analysis, or optimization that could greatly influence design decisions. For example, Group 1's submission included various formulas and calculations for current gain (hFE), power dissipation, and voltage drops, demonstrating their ability to apply them effectively. In contrast, Group 3's contribution mentioned a speed issue ("100 is too fast") without providing any numerical or formula-based explanations, indicating a more qualitative observation than a quantitative analysis. Although Group 3 also talked about gear ratios, hinting at some mathematical reasoning related to motion control, it seemed they did not explore the reasoning in depth. Overall, while students could use basic formulas and perform calculations, the results showed limited use of mathematics for more advanced design tasks, such as parameter optimization, system behavior prediction, or detailed quantitative comparisons of design approaches. The focus seemed to be on numerical accuracy rather than on using math as a robust tool for exploring and justifying design decisions.

Science integration is often the weakest aspect of engineering notebooks, with only 30% of entries explicitly linking scientific concepts to their projects. Although students frequently include scientific ideas in their work, they rarely explain or justify their design choices using scientific principles. For example, several entries from Group 3 lacked any scientific explanation, making it hard to assess their application of scientific concepts. Similarly, an entry from Group 5, shown in Figure 5, failed to

provide reasoning for the parachute's dimensions. This indicates that while students may understand certain scientific ideas related to a component, they have difficulty connecting this understanding to the broader design challenge. This underscores a gap in students' ability to translate their theoretical scientific knowledge into practical justifications for their design decisions. Although they may understand the underlying scientific concepts, they struggle to explain why a particular design decision is superior or necessary. This issue might arise from a lack of emphasis on applying scientific reasoning throughout the design process or from difficulties in communicating complex scientific ideas in a way that is pertinent to their work.

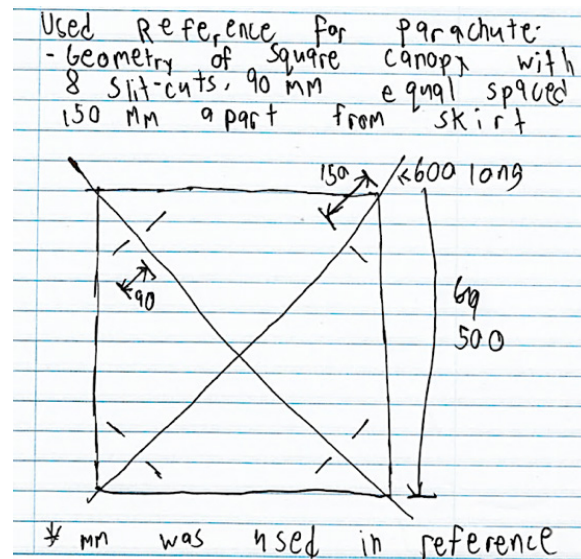


Figure 5. An example entry from Group 5 with no scientific explanation

The teacher in Cycle 2 played a more active role in regularly checking their engineering notebooks. This practice of monitoring and providing feedback on the documentation of STEM concepts likely prompted students to be more conscious and deliberate in their integration efforts, leading to the observed increase in entries for Science and Mathematics.

What are the students' perceptions of integrating STEM concepts in robotics CBL, particularly regarding its impact on their understanding and problem-solving abilities?

The thematic analysis of the students' responses revealed that their perception of how STEM integration enhanced their understanding and problem-solving skills aligned with the themes derived in Cycle 1, further solidifying their relevance and pervasiveness within the course experience. Student 1's statement, "*We integrated physics into our CBL project ... our group designed an airfoil to better control drag for our fixed-wing drone,*" exemplifies the application of abstract physics principles to a tangible, real-world engineering challenge within their CBL project. This suggests the course: **Bridged the Gap Between Theoretical Knowledge and Practical Application.**

Several responses underscored the **Development of Computational and Analytical Thinking Skills.** Student 2 noted, "*Programming involves a lot of trial and error, and I learned to solve some errors through constant testing and researching sources.*" This statement encapsulates the iterative nature of computational problem-solving involving systematic testing, error identification, and the analytical skill of seeking information to resolve issues. Similarly, Student 8 explained, "*This integration boosted my problem-solving skills since those concepts required much troubleshooting and required me to consider each factor in my work carefully.*" The emphasis on troubleshooting and carefully considering each factor directly reflects analytical thinking, breaking down complex problems into manageable components.

The Cycle 2 course’s implementation also fostered an environment that **Encouraged Reflection, Innovation, and Creative Problem-Solving**. Student 3’s realization that the integration “*allowed me to find multiple solutions to a single problem and express myself creatively in my work*” showcased their development of flexible and innovative thinking. Student 4’s elaboration on the encouragement to “*experiment with other Arduino components and make your own circuits that don’t necessarily follow the module planned for the day*” highlighted the profoundly personal and engaging aspect of creative exploration and self-directed learning within the course.

What challenges do students encounter in integrating STEM into their CBL projects?

In Cycle 2, the challenges for integrating STEM shifted. Although a lack of prior experience and knowledge in robotics was anticipated, the course duration was no longer an issue due to make-up sessions for class disruptions, ensuring the course met its scheduled meetings. The teacher in Cycle 2 offered a more thorough explanation of programming concepts during the Investigate Phase. Students expressed a continued desire for more hands-on learning and guidance. Student 3 specifically mentioned, “*I believe that there needs to be more effort and time put into teaching the Arduino code syntax for newcomers to the course.*” This highlights the essential need to address students’ varying levels of prior exposure from the start. Student 4 noted, “*Perhaps something that could be taught more is the coding side, as while we were able to use the technology, the code was usually copy-pasted from the module or on the internet ...*” This feedback identified a gap: students were meant to use the provided code as a basis for solving new problems, but they saw it as merely a copy-and-paste task. This points to the necessity of presenting these foundational activities as a vital initial step toward more innovative and independent applications. However, the difficulty in generating project ideas was resolved because students were assigned to work on their practical research projects, which they had conceptualized in the previous term.

A major new challenge identified was the “Challenges in Transitioning from Simulation to Real-World Application,” as outlined in Table 6. Student 1 explained this difficulty succinctly: “*... It’s straightforward to imagine how the components should interact, and while it’s somewhat more challenging, simulating these interactions in Tinkercad or Wokwi is also manageable. However, it’s an entirely different experience when attempting to construct your circuit in reality and encountering unreliable hardware or getting stuck ..., where each part functions independently but fails when combined.*” This statement clearly highlights the disparity between the controlled setting of simulations and the complexities of real-world implementation, underscoring the importance of providing students with troubleshooting techniques to help them effectively integrate hardware.

Table 6. New theme for challenges in STEM integration

Theme	Description	Code
Challenges in transitioning from simulation to real-world application	This theme encompasses the difficulties students face when moving from theoretical understanding and virtual simulations of robotics concepts to the practical implementation and physical construction of robotic systems.	Hardware Unpredictability Simulation-Reality Gap Conceptualization vs. Implementation

DISCUSSION

The quantitative data from both groups showed that students developed and achieved intermediate to proficient levels in STEM integration. While these scores suggest a successful facilitation of connections across fields, a deeper analysis reveals a disciplinary imbalance within the *Situated STEM Learning* framework (Kelley & Knowles, 2016).

PATTERNS OF STEM INTEGRATION

In both study cycles, the results clearly demonstrated that the CBL robotics environment effectively positioned Engineering Design as the key integrator for STEM education. This is consistent with the *Situated STEM Learning* framework, which suggests that engineering can offer a genuine context and platform for integrating other subjects (Kelley & Knowles, 2016). Students were not merely learning about engineering; they were actively engaging as engineers.

Engineering Design emerged as the primary integrator, appearing in over 90% of student entries across both cycles. This aligns with *Situated Cognition*, where the physical act of building a robot provides an anchor for abstract concepts. However, a significant gap remained in the integration of Mathematics and Science (initially 6% and 25%, respectively). Even with pedagogical adjustments in Cycle 2, such as metacognitive notebook reviews, Mathematics only rose to 35%.

Using the “block and tackle” analogy (Kelley & Knowles, 2016), while the Engineering and Technology “pulleys” were robustly pulling the load of learning, Science and Mathematics remained under-engaged. Students often bypassed scientific and mathematical justification in favor of trial-and-error. This finding challenges the assumption that robotics naturally integrates all four STEM disciplines equally, aligning instead with Roehrig et al. (2021), who argued that integration must be an explicit pedagogical goal rather than a passive byproduct of a hands-on task.

These results show that while robotics provides a powerful situated context for Engineering and Technology, Science and Mathematics remain latent disciplines that require deliberate, scaffolded prompts to move from the periphery to the core of the design process.

STUDENT PERCEPTIONS AND UNDERSTANDING

The qualitative feedback explains the high engagement levels despite disciplinary imbalances. Students overwhelmingly reported that the CBL environment made abstract concepts concrete, specifically bridging the gap between physics theory and practical application. This confirms the findings of Félix-Herrán et al. (2019), who found that CBL moves students beyond passive learning into active problem-solving.

Crucially, student perceptions were shaped by the organic formation of an informal *Community of Practice* (Lave & Wenger, 1991). As students navigated the Act phase, specifically debugging and programming, they engaged in legitimate peripheral participation. Students reported that being surrounded by experienced peers made the learning much easier, suggesting that their perception of their own problem-solving ability was bolstered by the social dimension of the classroom. This peer-to-peer exchange allowed novices to move toward the core of the robotics community, reinforcing the idea that STEM understanding is as much a social process as a cognitive one (Kelley & Knowles, 2016).

These results reflect that students perceive robotics-based CBL as a highly effective bridge to real-world applications. Their confidence in solving problems is significantly enhanced by the social support of a *Community of Practice*, which mitigates the technical hurdles of the hardware and software.

CHALLENGES IN INTEGRATION

A critical finding was the “beginner’s gap.” Despite high motivation and peer support, students felt overwhelmed by the technical complexity of hardware and programming. This frustration suggests that while an informal *Community of Practice* is valuable, it was not fully optimized. This reinforces the critique that an authentic context is necessary but insufficient; without foundational technical scaffolding, the hardware’s cognitive load can impede the cognitive goals of STEM integration.

These results unveil that the primary barrier to balanced integration is the high entry threshold of robotics technology. For novices, the social dimension of learning must be augmented with structured instructional scaffolding to prevent technical frustration from overshadowing disciplinary learning.

CONCLUSION

This study addressed the gap in understanding how K-12 students integrate STEM concepts in Challenge-Based Learning (CBL) robotics. The findings reveal that while a CBL robotics environment provides a highly effective, realistic setting for learning, it does not inherently ensure disciplinary balance. Students excelled in integrating Engineering and Technology, proving that the hands-on approach effectively situates learning; however, Science and Mathematics were notably under-applied. This suggests that the practical focus on building a functional product can overshadow the necessity for deep scientific and mathematical analysis. Consequently, the situated nature of robotics is a powerful but insufficient catalyst on its own. The constructionist process of “building to learn” must be intentionally scaffolded to pull abstract principles into the foreground.

The primary contribution of this research is the identification of the “beginner’s gap” and the disciplinary imbalance inherent in autonomous robotics projects. It challenges the flawed assumption that hands-on engagement automatically leads to holistic STEM integration. To bridge these gaps, pedagogical design must move beyond providing a context to providing strategic scaffolding, such as requiring scientific justification for design choices, to ensure the cognitive load of technical hurdles does not detract from disciplinary depth.

Authentic contexts provide the anchor for STEM learning, but explicit pedagogical scaffolding is the engine that ensures Science and Mathematics move from the periphery to the center of student innovation.

LIMITATIONS AND FUTURE RESEARCH

This study’s descriptive, mixed-methods design has two significant drawbacks. Firstly, without a control or comparison group, the results observed in STEM integration and student perceptions cannot be attributed solely to the CBL intervention. Although the design offers a comprehensive and detailed look at the student experience in the robotics setting, it does not permit causal conclusions. Subsequent research should use an experimental design to evaluate the effects of CBL in comparison to other teaching methods.

The study utilized a purposive sample of students who were voluntary members of a robotics club. These participants likely possessed higher intrinsic motivation and interest in STEM than the general student population, which may limit the generalizability of the findings to other contexts.

Additionally, given the qualitative nature and unique context of this research, a broader quantitative study could be undertaken to assess whether the observed uneven STEM integration pattern is consistent across populations and educational settings. Moreover, future studies should examine the effectiveness of particular teaching methods. For example, a comparative study could evaluate the influence of specific instructional strategies aimed at enhancing the integration of science and mathematics in a CBL robotics project. Lastly, a longitudinal study monitoring students’ development of STEM integration skills over several projects or years would offer valuable insights into how these abilities progress with ongoing practice and focused instruction.

ACKNOWLEDGMENTS

The research study presented in this paper forms part of the first author’s PhD dissertation at the Department of Science Education at the Br. Andrew Gonzalez, FSC College of Education, De La Salle University (DLSU), conducted under the supervision of Professor Lydia S. Roleda. Moreover, the authors would like to thank the Department of Science and Technology – Science Education Institute and DLSU for their valuable support in making this study possible.

DECLARATION OF CONFLICTS OF INTERESTS

The authors declare no conflicts of interest.

DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

In creating this work, we used the Writing Tools feature in macOS, part of the Apple Intelligence suite, and Grammarly to improve readability and language. Subsequently, we reviewed and revised the content as necessary and assumed full responsibility for the publication's content.

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