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Board 265: Engaging Students in Exploring Computer Hardware Fundamentals Using FPGA Board Games

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Engaging undergraduate and high school students in hands-on computer hardware fundamentals using FPGA board games

Introduction

Electronic devices are becoming indispensable in everyone's life. The computer hardware industry is demanding skilled professionals to design and physically implement devices to satisfy the market. The global chip shortage impacting the vehicle industry exemplifies the urgency for engineers qualified in the sophisticated manufacturing process behind electronic components [1]. However, misconceptions surrounding manufacturing jobs and the increasing initiatives to motivate students with engineering majors to focus on software-related topics such as artificial intelligence and blockchain are focusing students' interest away from hardware computing. The US Bureau of labor statistics projects a 5 percent growth in computer hardware engineers' job openings from 2021 to 2031. However, Data USA reported a decline of 27.9% in the total computer hardware engineering degrees awarded in 2020 [2].

With the job market demanding more professionals and the graduation rates decreasing, it is imperative to establish engagement and retention strategies to support hardware engineering-focused education initiatives. Hardware computing concepts are abstract, difficult to contextualize, and rely heavily on mathematics and physics [3]. Designing and developing hardware components is time-consuming, expensive, and frequently frustrating [4]. There is a need for hands-on, engaging instruction that facilitates the translation of those complex concepts into real-life situations [5]. However, hardware principles have been traditionally taught using a lecture-based approach, where instructors deliver instruction with minimal interaction or collaboration in the classroom [6].

Our project, funded by the NSF's Improving Undergraduate STEM Education (IUSE) program, aims to address this issue by developing a gamified curriculum that considers various aspects of meaningful and inclusive learning and includes novel hands-on approaches with a focus on computing hardware fundamentals. To create the curriculum, the project team is designing and developing a set of games played collaboratively using a field-programmable gate array (FPGA) board. Other components, such as switches to input data, LED arrays, and seven-segment displays, are also being added to the output, as depicted in Fig. 1. The primary goal is to enable an engaging, thought-provoking, and synergistic learning of the hardware aspects of computing for students from any engineering major. Each curricular module addresses a different fundamental concept of computing hardware, and collectively the modules provide a "peek inside the box" to construct an accurate perspective of what components constitute a modern electronic system and why. The PICABOO (Peek Inside your Computer hArdware BOx and explOre) curriculum leverages equitable practices, experiential learning, and collaborative, inquiry-based learning approaches to support engineering identity and engineering persistence. The curriculum will be offered in an elective undergraduate course for all engineering majors in two large public US universities and will be tailored to high school students' summer program experiences focused on STEM. No prior knowledge of hardware, electronic circuit design, and programming is required.

To perform a formative evaluation of our efforts, we conducted usability testing of the first two games. The objective was not to assess the implementation of the first two modules but rather to evaluate the usability of the games that serve as the foundation for the overall learning experience in the curriculum. Participants were seven neurodiverse and ethno-culturally diverse high school students (6 girls). The students were challenged to solve binary arithmetic and logic gates operations using the two PICABOO hardware games. The results indicate that despite the relatively low perceived usability, the games were engaging and helped students consolidate the hardware concepts. Improvements must be considered, such as placing the external LEDs and the FPGA switches in the same Least-Significant Bit (LSB) to Most-Significant Bit (MSB) position. This paper outlines the theoretical foundation of our curriculum and highlights the results and future design considerations for the games included in the curriculum.

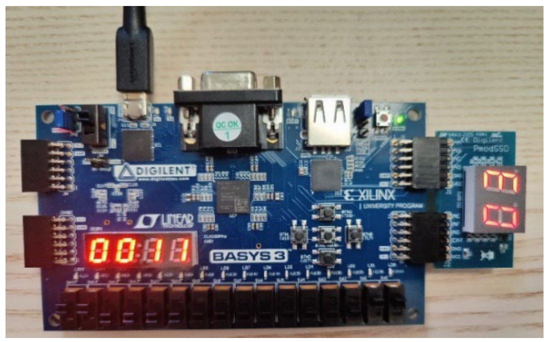


Figure 1. Example of the hardware setting

Theoretical Framework

We developed a conceptual framework for the PICABOO hardware curriculum that reflected our team's shared vision for the structure and the outcomes of our curriculum. Specifically, we aim to promote engineering identity and persistence by gamifying the learning experience to foster situational interest [7] and to support students' self-efficacy for engineering [8]. Additionally, educators' self-efficacy also influences their confidence in teaching hardware concepts [9]. The relationships between these theoretical foundations are illustrated in Fig. 2 and are incorporated into the design and development of the modules. The games are designed to be played on the hardware devices that are part of the gameplay segment of each module.

Interest in a particular activity is essential for cognitive processing and performance [10]. Situated interest refers to the learning environment or stimuli that sustain interest among a group of individuals [11]. The concept of situated interest is of great significance in education, particularly for those students who lack prior interest, knowledge, or skills in the subject matter [10]. Situated interest benefits include support for cognitive activities, working with computers, making inferences, focusing attention, integrating new information with existing knowledge, and overall learning improvement [11]. However, situated interest research has primarily focused on reading strategies, examining how text segment characteristics impact students' reading interests [12]. Studies examining strategies or sources to generate situated interest in computer science and engineering courses are scarce. The choice of activities and content can significantly affect students' situated interest, leading to potential cognitive and emotional changes. Therefore, it is imperative to develop activities that increase students' situated interest [7]. Triggering situated interest among students in complex hardware-related topics is critical in fostering well-informed electrical and computer scientists and engineers. Gamification techniques present promising opportunities in this area [13].

Situated interest is closely related to engineering identity. Engineering identity encompasses a student's self-perception and idea of themselves as an engineer, including their beliefs, attitudes, and values towards the field [14]. In an educational setting, promoting situated interest among students can help develop a stronger engineering identity. When students are enthusiastic and involved in their learning, they tend to view themselves as capable engineers, increasing their self-efficacy and self-belief in the field [8]. On the other hand, a robust engineering identity can also drive an increase in situated interest. As students identify as engineers, they become more motivated to learn engineering concepts and participate in related activities [15]. This creates a positive feedback loop, where the growth in situated interest and engineering identity complements each other, resulting in more equitable participation and success in the field of engineering.

The relationship between situated interest and equity is also fundamental to engineering education. Equitable and inclusive practices aim to create a welcoming and accessible learning environment for all students, regardless of their background or abilities, through the use of culturally responsive pedagogies [16] and Universal Design for Learning [17] principles. By creating a supportive and inclusive learning environment that fosters situated interest, educators can facilitate the development of a more equitable and diverse cadre of students pursuing careers in STEM fields, including hardware engineering [11].

Experiential learning is another critical component of the PICABOO curriculum and conceptual framework because it involves students actively participating in hands-on, interactive learning activities, allowing them to apply what they have learned in real-life situations [18]. This helps further increase student engagement and motivation. Related to experiential learning, inquiry-based learning is a student-centered approach to education that prioritizes asking questions, problem-solving, and pursuing knowledge [19]. Students are encouraged to take an active role in their learning through hands-on, experiential activities and making connections between what they are learning and their prior experiences [19]. Both approaches promote situated interest in engineering education by offering engaging and relevant learning experiences that connect the material to the student's lives and interests, thereby supporting students' self-efficacy for engineering.

Self-efficacy refers to an individual's belief in their ability to successfully complete a task or achieve a goal [20]. In the context of engineering education, self-efficacy refers to a student's belief in their ability to succeed in their engineering studies and eventually become a successful engineer. On the other hand, engineering persistence refers to a student's continued enrollment and successful completion of their engineering program, despite facing challenges and obstacles [21]. Research has shown that students with high levels of self-efficacy are more likely to persist in their engineering studies and overcome challenges [20]. This is because students who believe in their abilities are more likely to have a positive attitude toward their studies, be more motivated to learn, and have a greater sense of control over their academic outcomes.

An essential tool for promoting self-efficacy is the metacognitive practice of self-reflection, as it allows individuals to examine their experiences, thoughts, and actions and assess their abilities [20]. Through self-reflection, individuals can gain a deeper understanding of their strengths and weaknesses and identify areas where they can improve. This can help build confidence in their abilities and increase their sense of self-efficacy [20]. Additionally, reflecting on past successes and achievements can serve as a reminder of their capabilities and provide them with the motivation to tackle new challenges. Furthermore, reflecting on failures or difficulties can provide individuals with valuable opportunities to learn from their mistakes, identify areas for improvement, and develop new strategies to overcome challenges [20]. By providing opportunities for students to reflect on their experiences, the development and maintenance of self-efficacy is fostered, which can in turn lead to increased persistence in engineering and other fields.

Self-efficacy and reflection also play an essential role in determining teachers' persistence in teaching hardware engineering principles. When teachers have high self-efficacy for teaching in a specific knowledge domain, they are more likely to feel confident in their ability to teach the content and to engage students in learning, even when they encounter challenges [9]. Nurturing self-efficacy and persistence in teachers involves teacher professional development programs that facilitate the effective integration of technology, both software and hardware, into instruction. One framework that has been particularly helpful in achieving this goal is the Technological Pedagogical Content Knowledge (TPACK) [22]. TPACK defines the knowledge teachers need to successfully incorporate technology into their teaching, encompassing the integration of three key forms of knowledge: content knowledge, pedagogical knowledge, and technological knowledge [22]. Informed by the TPACK framework, it is possible to create meaningful implementation guides and educative materials that encourage self-reflection to foster teachers' persistence and teaching efficacy.

Drawing from the theoretical foundations discussed above, our conceptual framework for the curriculum includes modules that are all composed of five instructional events in the following order: (1) activation, (2) mini-lesson, (3) gameplay, (4) student-led work time, and (5) debrief.

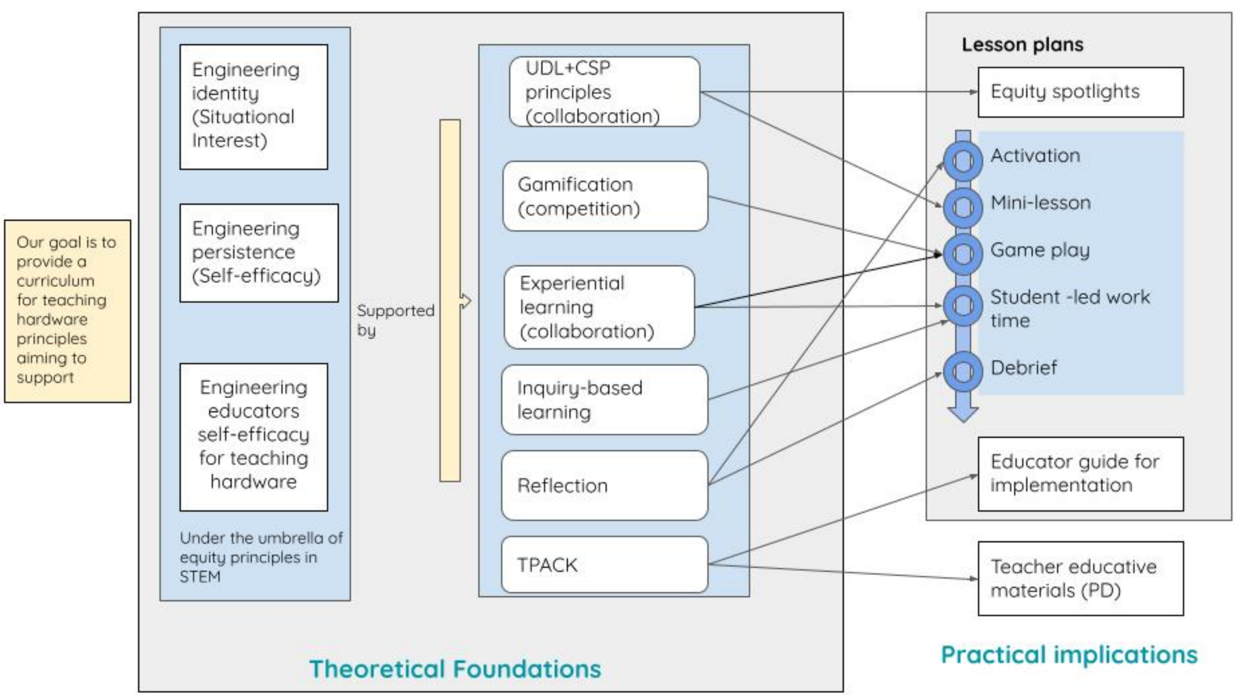


Figure 2. Curriculum conceptual framework

Method

Participants

Six girls and one boy in grades ten and eleven participated in the usability testing. Five attended two different US Southeastern public schools, and two were homeschooled. Participants were from four different ethnicities and had different math and computer hardware knowledge levels.

Games

One of the project's goals is to provide a comprehensive set of games designed to reinforce key concepts related to computing hardware. The set of games and their related concepts are depicted in Fig. 3. Each game focuses on one or multiple fundamental hardware concepts and involves hands-on tasks. The games collectively present a comprehensive understanding of hardware systems while allowing hands-on training in each step of the bottom-up hardware design process, from logic gates to building a computer. The games are part of the gameplay segment in the PICABOO modules. However, the games are standalone units that can be reused in other educational environments.

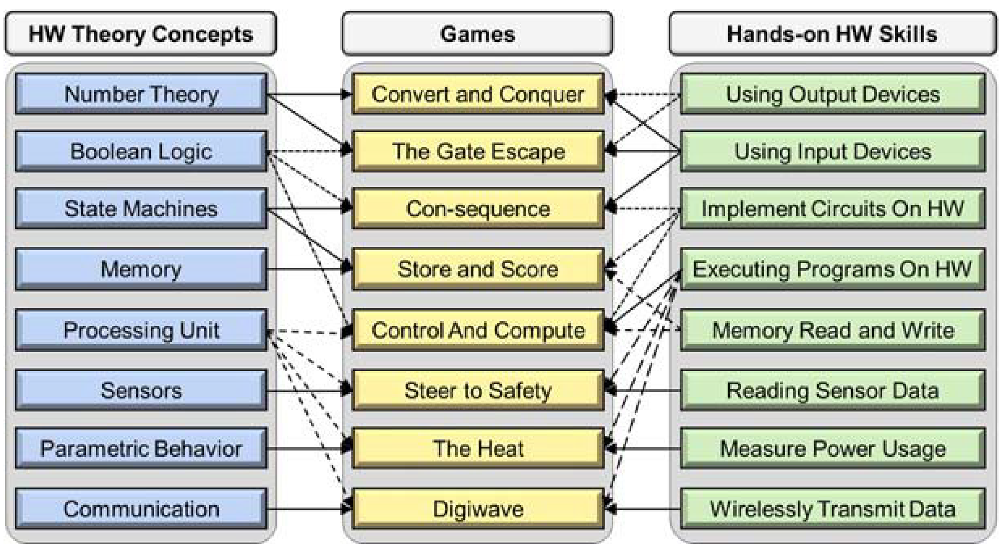
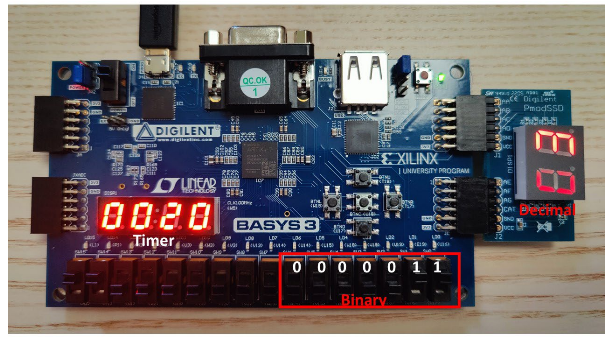
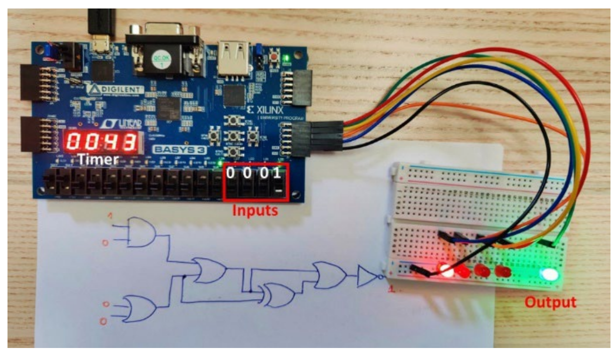


Figure 3. Games and hardware concepts

The usability testing involved the first two games. The games were played on a Digilent Artix-7 FPGA. The researchers completed the game design, synthesis, implementation, and Bit-stream file generation before the session. As part of the activity, the students uploaded the file in the FPGA and prepared the board according to the setting for the game (game one required a two-digit seven-segment display, and game two required a breadboard with LED lights). Since no prior knowledge was expected, the researchers delivered a short, interactive lecture on the topics required for playing the games. The first mini-lecture included explanations about the base-10 number system (decimal), the base-two number system (binary), strategies to convert from decimal to binary and vice versa, the difference between MSBs and LSBs, and the importance of binary numbers in hardware computing. The second mini lecture explained Boolean logic, truth tables, logic gates (NOT, AND, OR, NOR, XNOR, NAND), and combinational circuits inputs and outputs. Table 1 includes the game's instructions and a picture that exemplifies the hardware setting for each game.

Table 1. Games instructions

Game Title	Instructions	Setting
Game 1: Convert and Conquer	Convert the given decimal number to binary and send the response using the seven switches highlighted in the red box. The first switch on the right is the LSB, and the last from right to left is the MSB Verify the answer in the two-digit seven-segment display attached to the right side of the board	
Game 2: The Gate Escape	Calculate the output of a given combinational circuit and use the switches to verify the answer on the attached breadboard. The switches for the input are highlighted in the red box and correspond to the four red LED lights. The green LED displays the output (when the LED is on represents a one; otherwise, it is a zero)	

Competition and collaboration in the games

The games were designed to induce competition and collaboration among the students. The presence of competition has been known to drive male students, while the scope for collaboration generates interest in female students to perform better. Females prefer more relational and cooperative learning, while males prefer more competitive learning [23]. Also, females have been shown to be more active and persistent in collaborative learning environments [24].

To play the games, students were divided into three randomly generated teams (two pairs and a triad). Each team was challenged to complete the instructions for each game according to Table 1 in the least amount of time. The team that first completed the task correctly was given a point.

This was iterated over a certain number of challenges, and points were accumulated to define the winner. Students who are motivated through competition seek to win the game by performing fast and accurate operations. In addition, the teams were given the task of working together to complete a specific number of challenges within a restricted timeframe, regardless of which team was winning. This type of group challenge is particularly beneficial for students who are motivated by collaboration.

Measures and data sources

Participants completed a Systems Usability Score (SUS) survey after playing both games. The SUS is a well-known questionnaire to evaluate the perceived usability of a software or hardware product [25]. The survey measures users' overall satisfaction with a system based on ten 5-point Likert scale questions from strongly disagree (1) to strongly agree (5). The SUS survey is widely used as a simple, reliable, and valid measure of system usability. We added two open-ended questions to the survey aiming to expand on the main points of the like/dislike aspects of the games.

Also, we developed an observation protocol to validate students' behavioral, cognitive, and emotional engagement. One researcher observed the activity using the developed protocol. Finally, we conducted a semi-structured focus group to gather participants' opinions, suggestions, and aspects they enjoyed interacting with the hardware boards.

Results

The SUS score for each participant was obtained using the algorithm:

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X = (Sum of the points for all odd-numbered questions) – 5
Y = 25 – (Sum of the points for all even-numbered questions)
SUS Score = (X + Y) * 2.5
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The scores of all participants were averaged, resulting in an overall SUS of 61. SUS scores range from 1 to 100. According to the literature, scores below 68 are considered below average [26]. In addition, Table 2 provides each question's mean and standard deviation. For the particular purposes of this usability testing, analyzing the results of each question separately is a good strategy to identify potential improvements in the games.

Table 2. Descriptive statistics

	M	**SD**
1. I think that I would like to play the games frequently	3	0.76
2. I found the games unnecessarily complex	2	0.79
3. I thought the games were easy to use	4	0.53
4. I think that I would need the support of a technical person to be able to play the games	3	1.38
5. I found the various functions in the games were well integrated	4	0.53

6. I thought there was too much inconsistency in the games	2	0.76
7. I would imagine that most people would learn to use the games very quickly	4	0.58
8. I found the games very cumbersome to use	2	0.69
9. I felt very confident using the board for the games	3	1.21
10. I needed to learn a lot of things before I could get going with these games	4	0.98

To support the results from the SUS survey, we categorized the open-ended responses and results from the observation and focus group and obtained the following future design considerations for the games in the curriculum.

1. Considerations for each game setup
    a. The first game is engaging.
        i. The switches are interactive and work well with the seven-segment display.
    b. The second game needs to be improved.
        i. The breadboard adds complexity, and the relationship between the switches and the LED is not straightforward.
            1. MSB and LSB are hard to understand in the transition from the graphic circuit and the board.

2. General considerations for the games
    a. The point system engages learning.
        i. Adding a time limit as a group challenge generates anxiety.

3. General considerations for the FPGA board
    a. The board helps to think of the real-life applications of the hardware concepts.
        i. The FPGA board provides multiple means of representation.
        ii. The FPGA board is easy to use.
        iii. Using the board collaboratively is engaging.
4. Conceptual considerations
    a. The underlying hardware concepts of the two games were easy to understand.
        i. The mini-lecture was helpful.
            1. The discussion in the mini-lecture was engaging.
        ii. The board helped to consolidate the concepts.

Discussion and Conclusion

This project employs design-based research (DBR). DBR research design methodology improves educational practice through iterative analysis, design, development, and implementation as researchers and practitioners collaborate in real-world settings to develop contextually sensitive design principles and solutions [27]. In alignment with our project's objectives, the immediate focus of our DBR is to conduct a systematic investigation of the effective conditions for designing and implementing the PICABOO curriculum for improved hardware education that fosters engineering identity and persistence. The data collected in this usability testing will inform the redesign of the first two games and the design of the remaining games in the curriculum [27].

In general, it is promising that the students, with no prior hardware knowledge, reported a good understanding of the concepts and enjoyed interacting with the hardware boards in a gamified environment. The biggest challenge for the game design will be to reduce or scaffold the external components plugged into the main FPGA board. In game two, it is evident that the breadboard added complexity and inconsistency between the MSB and LSB switches arrangement and the LEDs order. This finding is fundamental as it indicates the utmost need to preserve consistency throughout the games in the curriculum on the approach to manipulating inputs and outputs in the board. The scopes for competition and collaboration must be shaped differently. The point system between teams fostered a safe, competitive environment. However, the timing generated anxiety and did not support the collaboration dimension. Finally, the interactive lecture was perceived as engaging, and participants appreciated being challenged with questions and discussion prompts. Experiential and active learning is an axial component of the conceptual framework of the PICABOO curriculum; therefore, this finding is a good indicator of the general project goals and expectations.

Acknowledgments

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